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SOLAR POWER SATELLITE

SYSTEM DEFINITION STUDY

Executive Summary

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16. Abstract

This document contains an Executive Summary of the Solar Power Satellite system Definition Study, Phase III. The Executive Summary Reports on all three phases of this study contract. The other documents of this set report only on Phase III results. Detailed reports on the earlier phases were issued at the conclusion of those phases.

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FOREWORD

The SPS System Definition Study was initiated in June of 1978. Phase I of this effort was completed in December of 1978 and was reported in seven volumes (Boeing document number D180-25037-1 through -7). Phase II of this study was completed in December of 1979 and was completed in five volumes (Boeing document number D180-25461-1 through -5). The Phase III of this study was initiated in January of 1980 and is concluded with this set of study results published in five volumes (Boeing document number D180-25969-1 through -5):

Volume 1 - Executive Summary (Summarizes all 3 phases of the study)
Volume 2 - Final Briefing
Volume 3 - Laser SPS Analysis
Volume 4 - Solid State SPS Analysis
Volume 5 - Space Transportation Analysis

These studies are a part of an overall SPS evaluation effort sponsored by the U.S. Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA).

This series of contractual studies were performed by the Large Space Systems Group of the Boeing Aerospace Company (Gordon Woodcock, Study Manager). The study was managed by the Lyndon B. Johnson Space Center. The Contracting Officer is David Bruce. The Contracting Officer's Representative and the study technical manager is Tony Redding.

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INTRODUCTION

This document is the executive summary report on the Solar Power Satellite System Definition Study, conducted by Boeing, General Electric, Grumman, Arthur D. Little, TRW, Brown and Root, and Math Sciences Northwest for NASA-JSC under contract NAS9-15636. This study activity was a part of the joint SPS evaluation initiated in 1977 by the U.S. Department of Energy and NASA, and completed in 1980.

The present study follows an earlier SPS definition study conducted under contract NAS9-15196 in 1977 and 1978. That study, in turn, stemmed from still earlier efforts. This report begins with a brief review of prior work to place current results in context.

Earlier Studies

In 1972, a study of SPS technical feasibility was carried out by a contractor team comprised of Arthur D. Little, Grumman, Raytheon, and Spectrolab, funded by NASA through the Lewis Research Center. The study found no feasibility barriers and developed a design concept that included a silicon solar array and a power transmitter using amplition microwave amplifiers.

Boeing began investigating the SPS concept in 1972. Our early studies reached three relevant conclusions:

1) Thermal cycle conversion offers an alternative to photovoltaic conversion.

2) Space transportation costs per kilogram of payload could come down to about 1/10 to 1/5 of the 1972 forecasts of shuttle costs if an SPS-capable transportation system could be developed.

3) The use of electric propulsion for orbit transfer could have significant cost advantages.

Additional studies and experiments, most of them funded by NASA over the period 1973 to 1975, established the feasibility of efficient energy transfer at microwave frequencies. In 1975 a demonstration conducted at JPL transmitted more than 30 kilowatts over a distance greater than a mile with a reception and conversion efficiency of 82 percent.

In the 1975 to 1977 time period, NASA conducted a technical assessment of SPS and began inhouse studies at the Johnson and Marshall Space Centers. The Department of Energy conducted its own assessment; SPS was discussed in congressional hearings. These activities led to development of the SPS Development and Evaluation Program Plan jointly sponsored by DOE and NASA. The principal milestones in this plan are:

Reference System Definition Report, October 1978 (Complete)
Preliminary Program Recommendations, May 1979 (Complete)
Updated Program Recommendations, January 1980 (Complete)
Final Program Recommendations, June 1980 (In Work)

As a part of this activity, solar power satellite system definition studies were conducted in order to support the milestones of this evaluation plan. These were to increase by roughly an order of magnitude the degree of depth of design and cost definition for SPS systems. Initial studies were performed by Boeing and General Electric for through the Johnson Space Center; and by Rockwell for the Marshall Space Flight Center. These studies began in 1977 and were completed in 1978. They created reference system designs including the solar power satellites, ground receiving stations, space transportation systems, space construction systems and other support systems.

Principal results of the Boeing/GE study were:

1) Silicon was recommended as reference, gallium arsenide as alternate: Silicon was seen as lowest risk, and cost differences were within the uncertainty band;

2) Rankine was recommended over Brayton: Thermal cycles presented construction and transportation problems when examined in detail; thermal cycles, however, provide a hedge against potential photovoltaics cost problems;

3) The klystron reference power transmitter design was developed: Detailed error analysis confirmed potential for efficient power transfer;

4) A winged heavy-life launch vehicle (HLLV) was selected over the ballistic option: The transportation cost for either was estimated as \$33/Kg to LEO; the winged option appeared to present less operational risk.

5) Electric self-power orbit transfer (modules of SPS's using their solar array output to drive electric thrusters) was selected over LO_2/LH_2 orbit transfer vehicles (OTV's) on the basis of lower cost.

6) An end-to-end space construction approach and facility concept was developed: Construction simplicity was a factor in selecting the SPS configurations.

7) Initial analyses of SPS maintenance and power grid compatibility were conducted: Maintenance throughout the year was selected as more economic than concentrating on equinox periods.

During the summer of 1978, following the study just discussed (and the companion study by Rockwell International for the Marshall Space Flight Center), NASA developed a reference system description to meet the October 1978 program milestone. Principal features of the reference system are as follows: 5,000 megawatt SPS, one transmitter—silicon and gallium arsenide solar cell options; klystron transmitter—magnetron and solid state recognized as potential options; GEO construction with independent electric OTV; two-stage vertical take- off, horizontal landing rocket HLLV. These decisions were made in parallel with the beginning of the current Boeing study for NASA Johnson Space Center. As these decisions occurred, the present study adopted them. Alternatives were also examined, including solid-state and laser power transmission and HLLV options aimed at reducing nonrecurring cost.

Study Team

The present study was initiated in July of 1978, under JSC technical direction. The JSC technical manager was H. Benson. The study team includes Boeing as prime contractor and Arthur D. Little, Brown & Root, General Electric, Grumman, Math Sciences Northwest, and TRW as subcontractors. The study team leaders for each contractor are named in Figure 1.

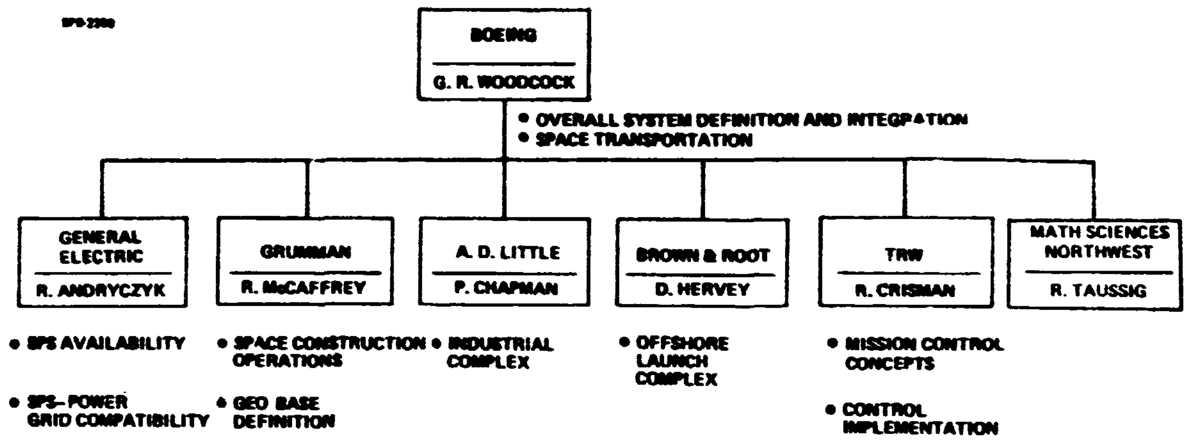

Figure 1 — Study Contract Team Organization

TABLE I

PRINCIPAL STUDY ACCOMPLISHMENTS AND CONCLUSIONS
(Subcontractor contributions are noted)

Task	Phase	Accomplishment	Conclusion
Critique and Update Reference System	I	Developed in-depth critique of baseline	No fundamental flaws but several design deficiencies that should be corrected
	I	Corrected design deficiencies	No significant change in mass, cost, or efficiency
	I	Evaluated electric orbit transfer vehicle in comparison with self-power	Cost & risk differences not decisive; adopted DOE/NASA reference (EOTV)
	III	Analyzed sensitivity of Electric OTV to annealing assumptions and thermal effects in low Earth orbit	o EOTV is viable o If annealing is not developed, additional array shielding (thicker covers and substrate) should be used. o Hydrogen MPD is potentially attractive backup to argon ion; more MPD research needed.
	II	Updated reference design with mass & cost estimates at WBS Level 5/6	o No significant change in mass or cost o Information management and control needs a hierarchical computer network with internal diagnostics and fault correction
Examine Alternatives to Reference System	II/III	Defined solid-state SPS option	o Antenna-mounted approach is viable o Solid state transmitter is thermally limited to 2500 megawatts delivered. o At 2.5 Gw delivered the solid state SPS is approximately 20% more costly per unit power than the klystron reference system. power as the Klystron system o Developed transmitter module concept compatible with 8 kV power distribution o Potential technical advances make solid state sufficiently attractive to merit further analysis & research

TABLE I (Continued)

PRINCIPAL STUDY ACCOMPLISHMENTS AND CONCLUSIONS
(Subcontractor contributions are noted)

Task	Phase	Accomplishment	Conclusion
Alternatives (Continued)	III	Analyzed laser power transmission options (Boeing, Math Sciences NW)	o Laser options can transmit small blocks of power, i.e. 10 to 1000 megawatts o Capital cost per KW is higher than microwave systems by roughly a factor of 2. o Laser systems can't get through inclement weather. o Free electron laser is most promising area for research.
	III	Evaluated Shuttle-derived SPS Transportation system	o Recurring cost roughly twice reference system o Principal penalty comes from chemical rather than electric orbit transfer o Non-recurring savings comparable to small HLLV
	III	Defined and evaluated a smaller Heavy Lift Launch Vehicle (HLLV)	o Selected an 11x11 meter square by 14-meter long payload bay with payload capability of 125 metric tons. Non recurring savings exceed $5 billions compared to reference HLLV o Higher recurring costs add 3% to SPS costs o Small HLLV recommended as SPS reference
Construction and Maintenance	I	Evaluated six construction approach options (Grumman)	Selected 4-bay end builder as best overall approach
	II	Defined construction base (Grumman)	o Overall approach is sound o Construction crew of 440 for 2 SPS/year o Construction cost is about 10% of SPS cost
	I	Developed low cost rectenna construction design and approach (GE)	o Rectenna costs dominated by materal costs o Rectenna costs reduced; $520/KWe (1979 $)

TABLE I (Continued)

PRINCIPAL STUDY ACCOMPLISHMENTS AND CONCLUSIONS
(Subcontractor contributions are noted)

Task	Phase	Accomplishment	Conclusion
Construction (Continued)	II	Updated & extended maintenance analysis (Boeing for SPS; GE for rectenna)	o Maintenance cost is about 0.3¢/Kwh
	III	Analyzed construction requirements and effects for (a) solid state SPS; (b) laser SPS (IOPL option); (c) small HLLV (Grumman)	o Construction productivity losses associated with solid state SPS and small HLLV are minor o IOPL laser SPS is a major construction productivity problem because of concentration complexity (Does not apply to other laser options)
Industrial Complex	I	Identified production capacity issues (ADL)	Major issues are: o Photovoltaics o Klystrons o Composite structural materials o Rectennas
	II	Scoped industrial complex needs (ADL)	o Problems are tractable o Ground transportation not a problem
	II	Developed industrial complex cost estimates (ADL/Boeing)	Costs of the required industrial complex are affordable in a context of affordable SPS electricity
Launch Complex	I	Evaluated Equatorial Launch	o Found no major performance advantage o Recognized potential need to eventually move from KSC because of traffic level
	I/III	Defined KSC launch site requirements	o Launch & recovery site costs of added facilities: 5 Billion (reference HLLV) o KSC capable of handling SPS launch rates up to ≃ 10Gw/yr Launch & recovery site costs for small HLLV: 1.9 Billion
	II	Developed offshore launch complex concept (Brown & Root)	o It's feasible o Probably least cost way to develop equatorial launch capability

TABLE I (Continued)

PRINCIPAL STUDY ACCOMPLISHMENTS AND CONCLUSIONS
(Subcontractor contributions are noted)

Task	Phase	Accomplishment	Conclusion
Operations	I/II	Analyzed depressed HLLV trajectories	Trajectories that minimize poten- environmental concerns result in less than 10% payload penalty
	II	Developed integrated operations approach and definition	o Operations management not a cost driver o Communications requirements can be met without high costs; need two relay satellites at GEO
	III	Analyzed integrated operations for options	o Solid-state comparable to reference system - slightly higher recurring costs but lower maintenance costs o Lasers using optical concentrators (OPL's) incur severe construction cost penalties. Other lasers incur modest penalties due to small unit size o About half of small HLLV cost penalty arises from operations cost incurred due to smaller payload size & mass capability
SPS/Ground Power Network Integration	I	Examined rectenna siting	o Adequate siting opportunities exist
	I	Updated rectenna description (GE)	o Energy intensive materials use can be minimized
	I	Updated rectenna/network interconnect (GE)	o Rectenna is compatible with either HVAC or HVDC
	II	Updated SPS reliability and availability (GE)	Availability ≃ 0.92

TABLE I (Continued)

PRINCIPAL STUDY ACCOMPLISHMENTS AND CONCLUSIONS
(Subcontractor contributions are noted)

Task	Phase	Accomplishment	Conclusion
SPS/Ground (Continued)	II	Assessed SPS LOLP, unit size, control, and reserve margin requirement (GE)	o Unit size not a problem o SPS cannot contribute to frequency control unless special synthesis techniques are developed o SPS will not have a major impact on reserve margin requirements
Technology Advancement & Development	I/II	Analyzed SPS development	o Identified & characterized 5-phase program structure o 5-phase program facilitates risk management o Overall non-recurring cost is affordable based on projected SPS market; will be repaid by taxes from operating units
Costs & Schedules	I/II	Developed overall non-recurring and recurring costs & schedules	o Costs relatively insensitive to metholodogy details o 18-20 years needed to commercialize SPS
Exploratory Technology	I	Tested Laser Annealing of 50-μm solar cells degraded by proton irradiation	Recovery of about 50% was consistently demonstrated
	II/III	Demonstrated a two-way fiber optic phase distribution link at 980 MHz	o Fiber optics phase distribution is feasible and advantageous
	II/III	Demonstrated a 4-way power combiner antenna element for solid-state SPS application.	o Low-loss combining was demonstrated
	II/III	Fabricated and tested a 200-slot, 10-stick slotted waveguide antenna element	o High efficiency demonstrated as well as can be determined within 0.4 db measurement uncertainty

Table 2—Critique Summary

CRITIQUE ITEM	RESOLUTION
SPS Large Unit Size	Examined by GE; not a problem in SPS time frame
Space Debris from Construction Operations	Debris sources not identified; secondary or incidental sources should be worked in Engineering Verification
Long-Term Life of SPS Materials	Research Phase Emphasis
Lack of Definition of Flight Control and Computing Systems	Definition improved in present study
Plasma/High Voltage Interaction Potential	Research Phase Emphasis
Solar Array Performance, Degradation, and Annealing	Initial degradation and annealing tests confirm general approach; much emphasis required during research program.
Lifetime of Power Electronics	Design changed to eliminate identified failure mode

STUDY RESULTS

The study was comprised of eight tasks and was conducted in three phases. The accomplishments and conclusions are summarized in Table 1.

The following discussion follows the outline of the task activities summarized in Table 1.

REFERENCE SYSTEM ANALYSES

Critique Summary

The study began with a critique of the 1978 reference design. **The critique concluded that the SPS concept had no fundamental technical flaws, but identified several design deficiencies.** The critique was conducted by an independent panel of technical experts. Roughly 100 critique items were developed, some of an incidental nature. A number of significant items were identified and are summarized in Table 2. Of particular importance were concerns regarding materials and power electronics lifetime, and plasma-high voltage interactions.

In addition to these items, there were certain critique items of an environmental nature. These were previously known and are included in DOE environmental assessment research. They are outside the scope of the present systems definition study.

Construction Location and Orbit Transfer

As a part of the baseline system task, construction location and orbit transfer options were reviewed. The three concepts compared were: (1) LEO/SPM: construction of the SPS in low Earth orbit and use of self-power to move SPS modules to GEO, as proposed by the earlier Boeing/GE study; (2) LEO/SPM/EOTV: the same with use of electric orbit transfer vehicles (EOTV's) to return self-power propulsion equipment to LEO for reuse; (3) GEO/EOTV: construction at GEO with use of EOTV's for all cargo orbit transfer. Cost trends with time for the three orbit transfer/construction locations options are shown in Figure 2.

Although a nonrecurring cost advantage was seen for LEO/SPM, the overall trade was too close to call; the DOE/NASA baseline (GEO/EOTV) was retained.

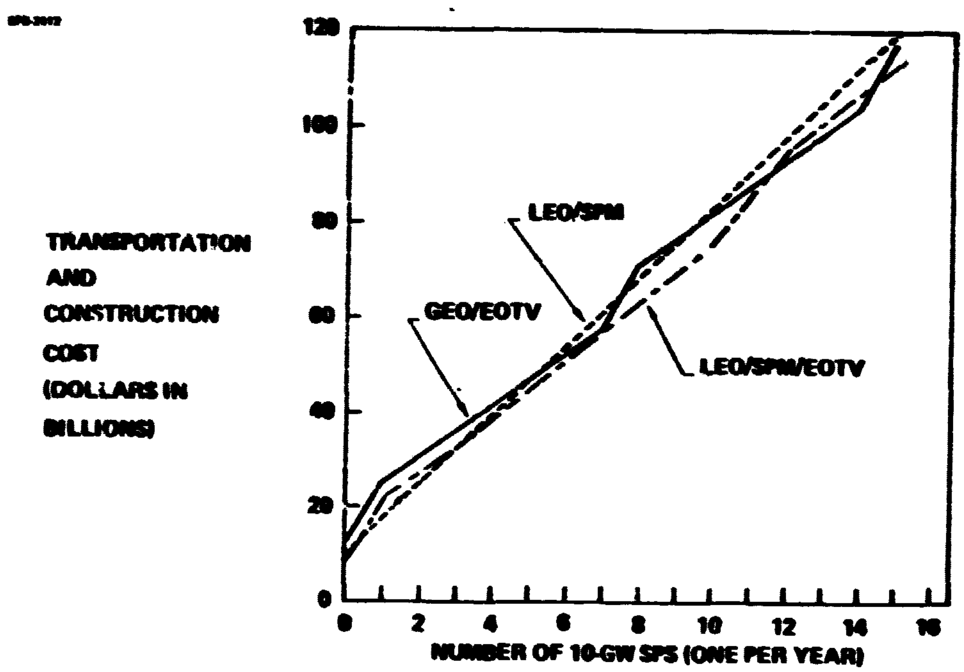

Figure 2—Cumulative Cost Comparison

The Phase I analyses of the electric orbit transfer vehicle assumed the solar array output would be equivalent to that expected at geosynchronous orbit without significant thermal radiation effects due to the proximity of the Earth. Orbit transfer propulsion operations near the Earth will have solar array temperatures as high as 70°C. The result is a reduction in output from the solar array.

A second concern is the start-up time for the electric thrusters. Estimates of the time required to start electric thrusters span a wide range. A reasonable estimate is 10 minutes. This is also similar to the time required to stabilize the solar array temperature after emergence from shadow. An orbit transfer simulation was used to predict orbit transfer performance with thermal and time delay effects included. Simulation results were incorporated into an EOTV systems model as a part of performance and required electric power calculation algorithms.

The EOTV mass is calculated from high-level mass estimating factors relating the solar array mass, the power processor mass, thruster mass, and auxiliary propulsion masses to required electric power. Cost estimating includes consideration of investment cost, HLLV lift cost, and EOTV amortization and trip time costs.

Six cases were investigated. The first was the reference EOTV case with 75 micron cover glasses, argon ion thrusters with solar array annealing. The second was the same system without solar array annealing. Array degradation is so rapid that one may expect no more than 3 trips. Increasing cover glass thickness allows substantially more trips (up to 10). Performance with and without thermal effects amd time delays were compared for this case.

The Earth's magnetosphere may be affected by the high-power electric propulsion plumes. It is not presently known if this is a significant problem, but if it is, mitigation by use of hydrogen in place of argon as propellant has been proposed. Arc jet or magnetoplasmadynamic (MPD) thrusters would be used rather than ion thrusters. Three MPD cases were investigated.

Figure 3 compares costs of the various systems investigated to chemical orbit transfer vehicle system cost, all based on the same HLLV launch cost estimates. In all cases, the EOTV exhibits lower recurring cost than the chemical OTV system.

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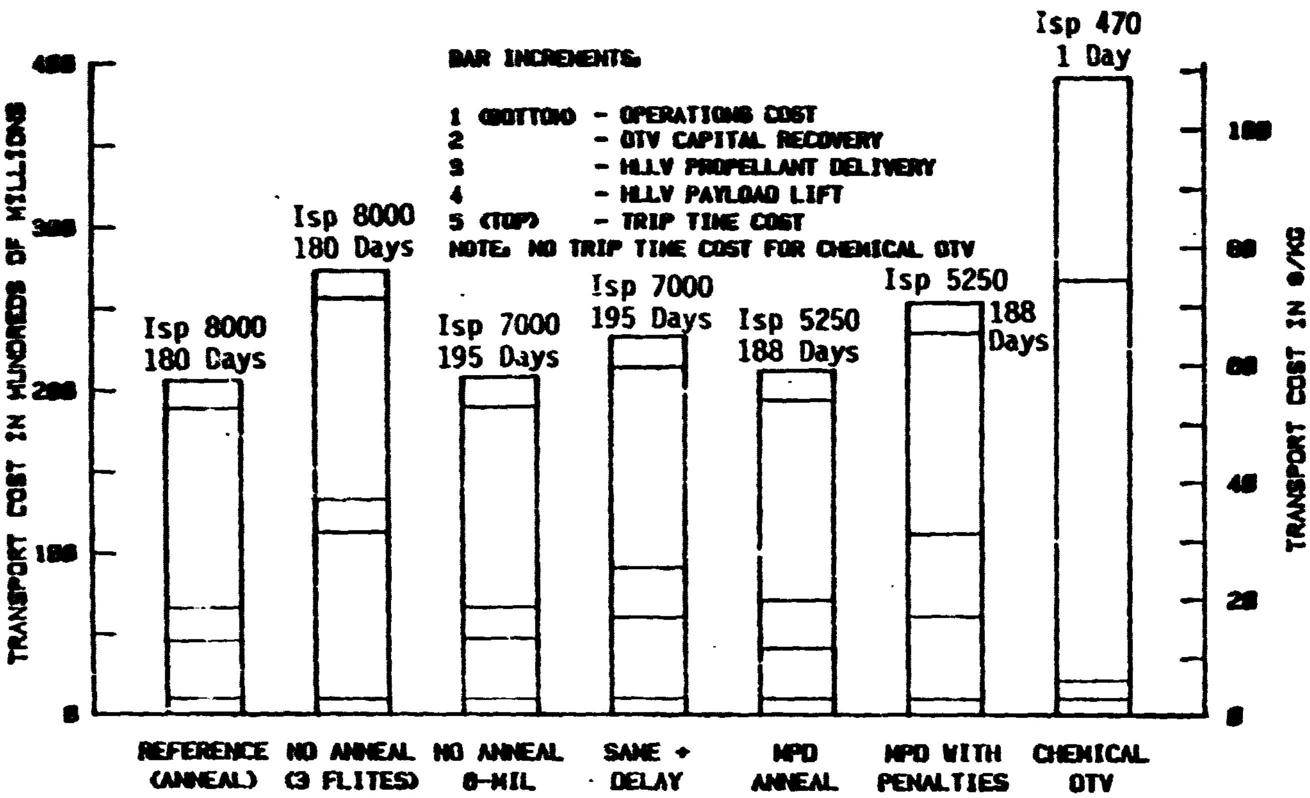

Figure 3—SPS Transportation Cost Comparison

Reference System Definition Update

The reference system update resulted in little change in mass and cost and provided important improvements in design understanding in several areas.

During Phase II, the reference system definition was updated to incorporate correction of design deficiencies and improved definition in some of the subsystem areas. As a part of the system definition update, the level of definition was carried to WBS Level 5 on the satellite, with details at Level 6 in most areas. Figure 4 illustrates a typical definition item. The mass of each box and cable was estimated and the mass contribution to each satellite was estimated from the number of each item per satellite.

The updated definition provided additional detail especially in the following areas:

- Maintenance provisions
- Phase distribution and subarray control circuits
- Information management and control

An important change from the earlier definition is that the phase control system was modified by providing an uplink receiver and phase conjugator for each klystron rather than for each subarray. Two benefits result:

- The beam efficiency is improved by about 1%, with attendant value of the order of \$100 million, exceeding the cost of the order of \$50 million. (The efficiency chain was updated from earlier studies as this small improvement is well within the uncertainty band.)
- The grating lobes are reduced in number and intensity, as shown in Figure 5. The strongest grating lobes are reduced from roughly 40 microwatts/cm^2 to less than 2 microwatts/cm^2.

A significant set of conclusions was reached regarding information management and control: (1) The quantity of data to be handled demands a hierarchical computer network

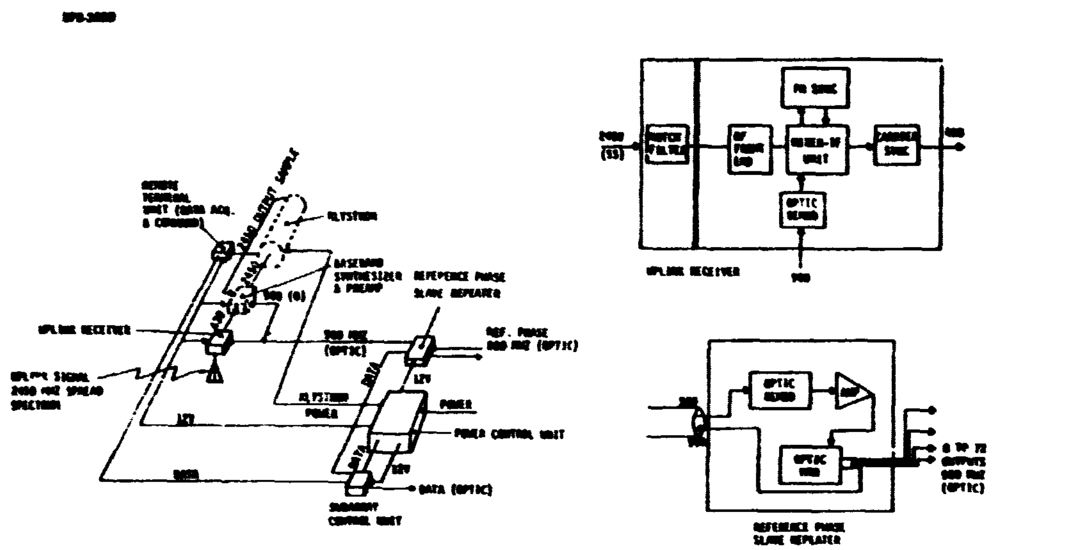

Figure 4 – Typical System Definition at Level 5 (WBS 1.1.2.2.5, Subarray Control Circuits)

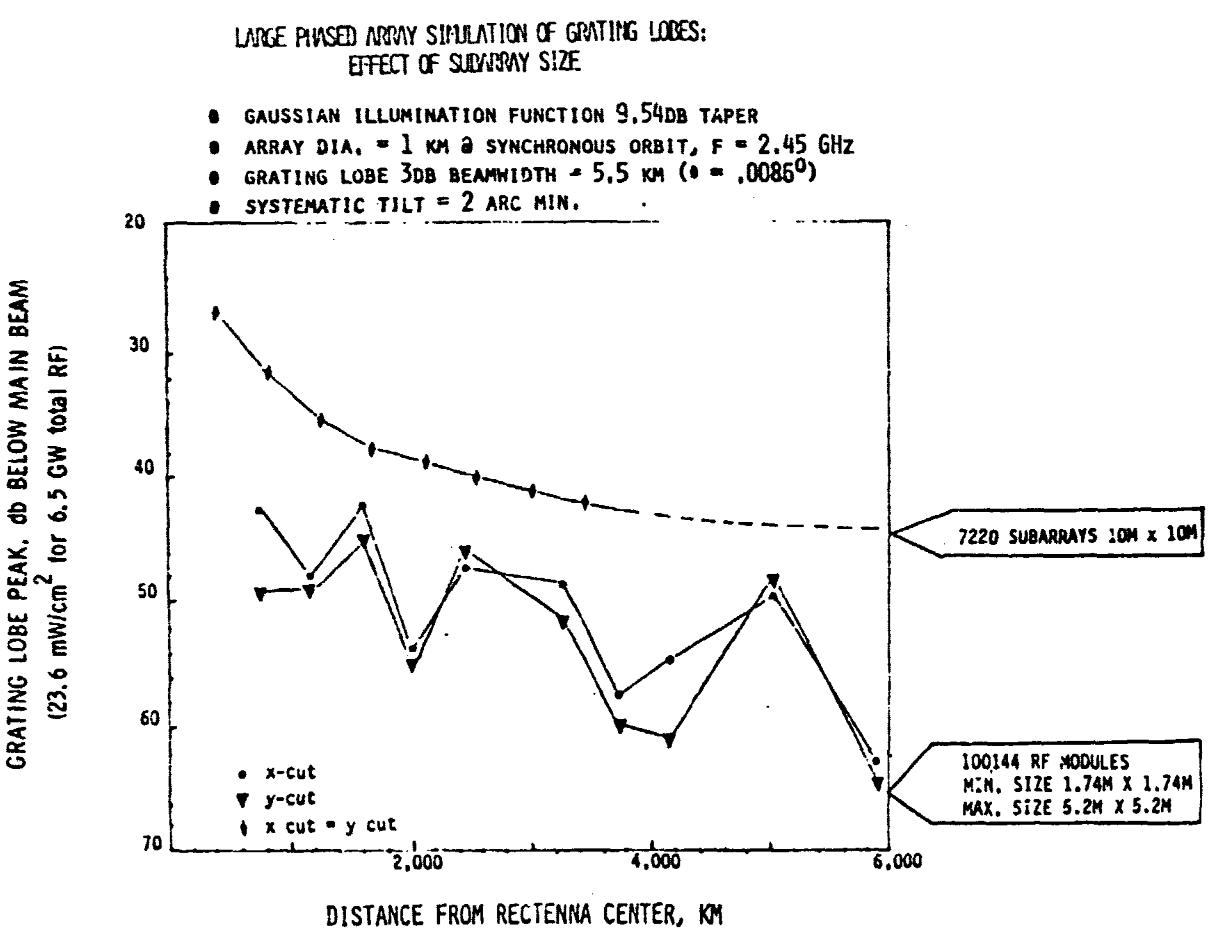

Figure 5 – Large Phased Array Simulation of Grating Lobes: Effect of Subarray Size

with internal diagnostic and fault correction capability; (2) The resulting system should not pose major technical or cost problems in the time frame of interest.

REFERENCE SYSTEM DESCRIPTION SUMMARY

The composite drawing of Figure 6 illustrates the main features of the present reference design silicon solar cell SPS. The solar array consists of glass encapsulated 50-micrometer silicon solar cells suspended in a space frame cubic trusswork of 128 bays, each 667.5 meters square and 470 meters deep. The array area of 49.6 square kilometers generates 8766 megawatts of dc electricity at 44 kv. This electric power is conducted by an arrangement of ten pairs of busses to the slipring where it is transferred to the power transmitter. The transmitter converts the electric power to 6700 megawatts of radiated RF power at 2,450 megahertz; a total of 101,552 high-efficiency klystron power transponders conjugate and amplify the uplink phase control signal and return it to Earth as a power beam. Each klystron is individually phase-controlled to maintain precision beam forming and high gain. The SPS solar array is maintained sun-facing by an electric propulsion attitude control system and the transmitter is maintained Earth-facing by a combination of turntable drive coarse pointing and control-moment gyro (CMG) fine pointing.

The complete SPS system includes not only the satellite, but also space construction and support systems: a base in low Earth orbit (LEO base) for construction of electric orbit transfer vehicles (EOTV's) and for service as a space transportation staging and logistics base; a base in geosynchronous orbit (GEO base) that constructs the SPS's and serves as a maintenance support base; and the mobile maintenance systems that visit operating SPS's to provide periodic maintenance. In addition, space transportation provides crew and cargo transportation with four vehicles: Heavy Lift and Personnel Launch Vehicles, and Electric (Cargo) and Personnel Orbit Transfer Vehicles. Finally, on Earth there are SPS receiving stations and the industrial and transportation infrastructure and integrated operations management that support the entire enterprise. The entire system is symbolized by Figure 7.

A further aspect is provided by a timewise slice. The SPS program, beyond the present phase of paper-study evaluation supported by a few exploratory technology investigations, is projected to include five phases as summarized here:

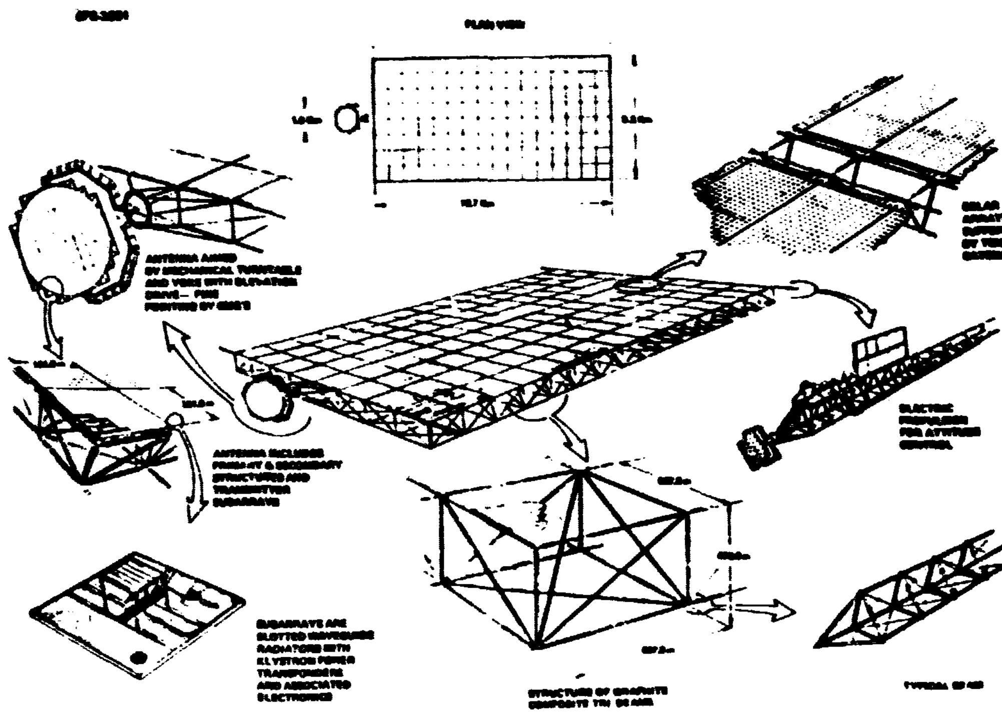

Figure 6 – SPS Silicon Solar Array Reference Design Concept

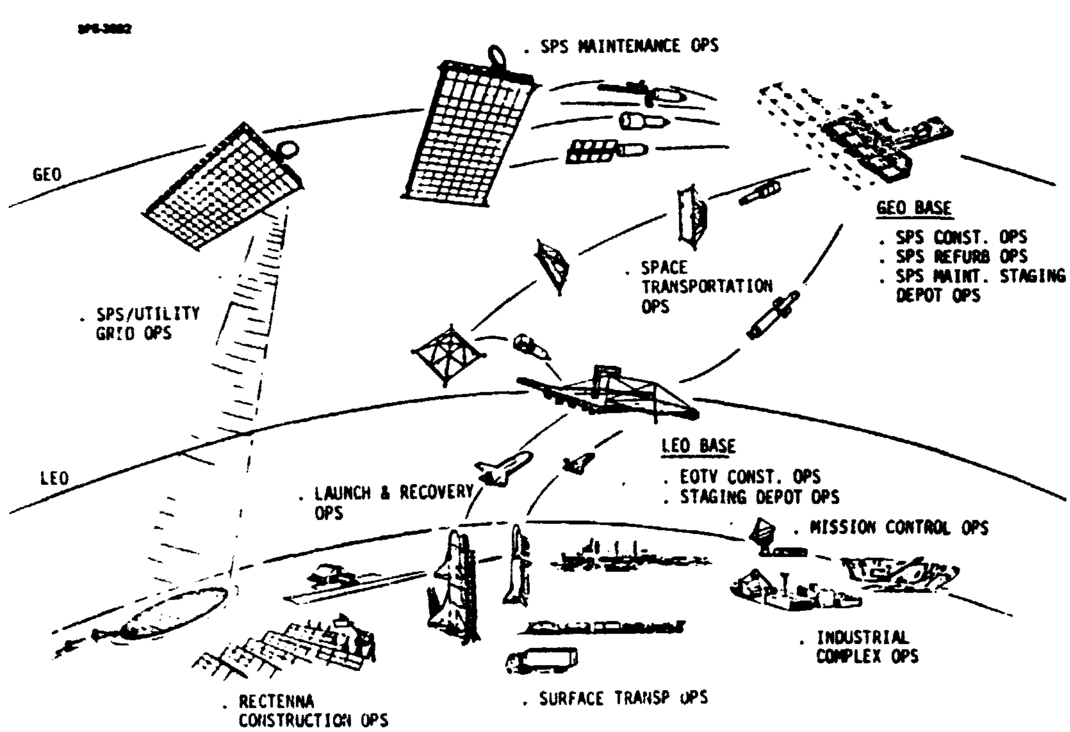

Figure 7 -- Integrated SPS Program Operations

- o Research—Evaluate and select SPS technologies; resolve technical, environmental and socio-economic issues;
- o Engineering verification—demonstrate conversion of SPS technologies into practical engineering hardware;
- o Demonstration—demonstrate end-to-end operational suitability of SPS as a baseload electric power source;
- o Investment—create the industrial base to produce SPS generating capabity at 10,000 megawatts/yr;
- o Commercial production—install and maintain 300,000 megawatts of SPS generation capacity over 30-year period

The mass and cost results of the reference system update are tabulated in Tables 3 and 4. Table 3 presents mass and recurring cost elements for the satellite. Average SPS recurring costs including all WBS elements are summarized in Table 4. The cost estimating method for satellite hardware implicitly includes amortization of factories and equipment, so an appropriate amount has been subtracted here, since these investments were identified as a discrete non-recurring cost included under the investment phase of the program.

Determination of the cost of an SPS to a utility requires specific definition of financial and management scenarios. A representative figure may be obtained by adding back the implicit amortization and then adding 15% for financial costs such as interest during construction; the result is $14.8 billion, just under $3000/KWe in 1979 dollars.

ALTERNATE SYSTEMS

Solid State Transmitters

It was concluded that (1) antenna-mounted solid-state transmitters will work; (2) they optimize at 2500 megawatts net ground output; (3) the solid-state approach is potentially as cost-effective as the Klystron approach at lower power levels and should be included in subsequent SPS research.

Table 3 – SPS Hardware Mass and Cost Summary

	MASS	COST	$/KG
SPS TOTAL	50,984	4,945.9	
ENERGY CONVERSION	27,665.9	2,859.6	
STRUCTURE	4,654	448.2	96
SOLAR BLANKETS	21,144.9	1,987.8	94
POWER DISTRIBUTION	1,246	149.9	120
MAINTENANCE PROVISIONS	621	273.7	440
POWER TRANSMISSION	13,628.9	1,768.7	
STRUCTURE	324.3	25.6	79
SUBARRAYS	10,389.1	889	86
POWER PROC. & DISTR.	2,538.7	324.1	128
PHASE DISTR.	12.3	12.5	1016
MAINTENANCE PROVISIONS	230.2	503.9	2189
ANTENNA MECH POINTING	134.3	13.6	101
INFO MGMT & CONTROL	95.6	48.0	
COMPUTERS	4.5	30.7	6822
CABLING	91.1	17.3	190
ATTITUDE CONTROL & STA. KP.	212.1	160	
HARDWARE	142.1	160	1126
PROPELLANT	70	-	
COMMUNICATIONS	0.18	8	44,000
INTERFACE	235.6	101.6	431
GROWTH ALLOWANCE (22%)	9,146	Carried at Next Level	

Table 4 – SPS Recurring Cost Summary (1979 Dollars)

SPS HARDWARE AS COSTED	4946	
LESS IMPLICIT AMORTIZATION OF INVESTMENT	473 4473	(Half of 10.61% per annum on 8924 M for factories and production equipment)
SPACE TRANSPORTATION	3120	Based on SPS mass with growth'
CONSTRUCTION OPERATIONS	961	Includes 10 support people on the ground per space worker as well as construction base spares
GROUND TRANSPORTATION	35	
RECTENNA	2578	
MISSION CONTROL	10	
PROGRAM MANAGEMENT & INTEGRATION	495	Equivalent to 14,000 direct people
COST ALLOWANCE FOR MASS GROWTH	760	17% of net SPS hardware cost
TOTAL DIRECT OUTLAY	12,432	

During Phase I of the study, parametric analyses of solid state SPS's were developed, indicating possible advantages of the solid state approach for power outputs in the 1000-2500 megawatt range. A power combiner module concept was also developed, well-suited for implementation in an SPS similar to the reference configuration.

Early in Phase II the parametric analyses were extended to investigate solid-state "sandwich" configurations. ("Sandwich" configurations employ solar cells and microwave amplifiers in a sandwich back-to-back configuration. Sunlight is concentrated on the array by plastic film reflectors. Sandwich configurations are thermally limited to low powers.) These were compared with separate-antenna options and found to be potentially interesting in the low-power (≃1500 megawatts) range but offer no unique advantages, if a solution to the power supply problem for separate-antenna options can be developed. The sandwich configurations are mechanically complex and pose construction complexity issues.

A solid-state reference configuration was created in Phase II. Investigation of series-parallel connections of the solid-state amplifiers as regards dc power supply indicated this to be a promising approach. The solid-state configuration, shown in Figure 8, is similar to the reference configuration with the following major differences:

- The power delivered to the grid is 2500 megawatts rather than 5000 megawatts.

- The array size is 8 x 9 bays rather than 8 x 16 bays.

- The array voltage is 10 KV rather than 44 KV. This array voltage provides ±4.4 KV to the transmitter after I^2R drop in the power conductors.

- The transmitter aperture is 1.4 km rather than 1.0 km.

- The transmitter employs gallium arsenide FET's rather than klystrons.

A mass estimate for the solid-state configuration is presented in Table 5. The mass is about 60% of the klystron reference system although the power is only 50%. The lower distribution voltage leads to high losses (thus proportionately more solar array) and a heavier distribution conductor system. The direct dc system has less mass and cost than

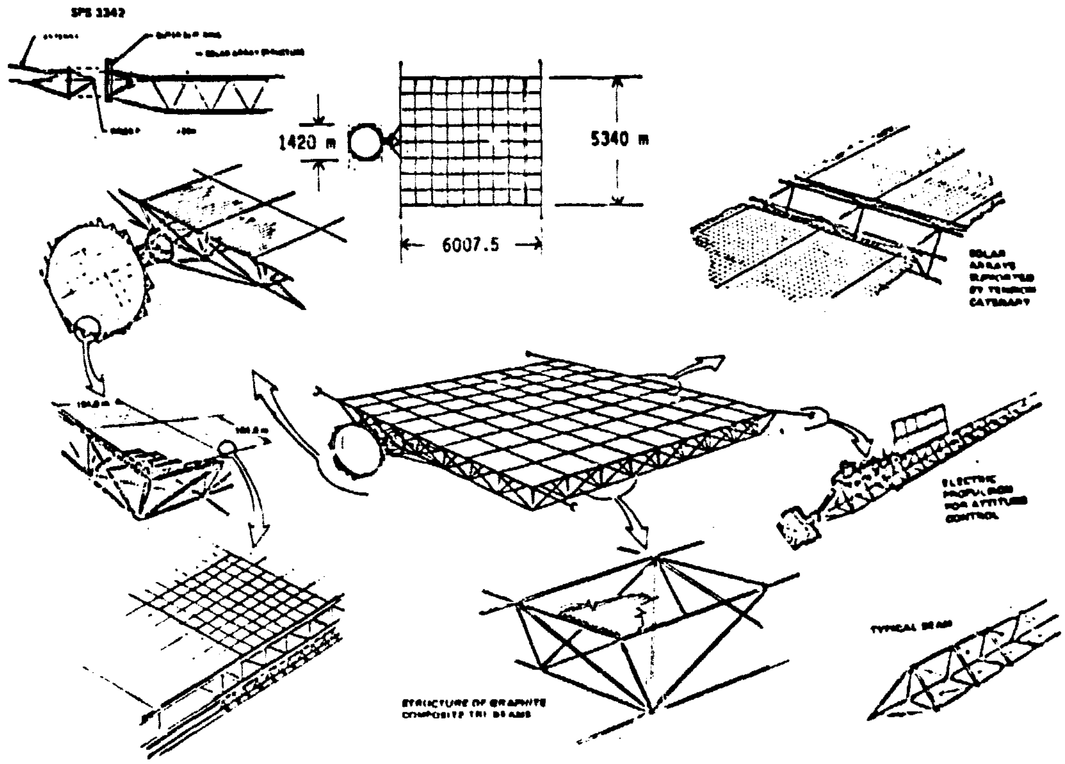

Figure 8—2.5 GW Solid State SPS Configuration

Table 5 — Solid State SPS Mass and Cost Summary

		MASS (MT)	ESTIMATING BASIS	(COST ($M)
1.1	SPS	30,301		3,890
1.1.1	ENERGY CONVERSION	17,037		1,662
1.1.1.1	STRUCTURE	2,333	Detailed Estimate	225
1.1.1.2	CONCENTRATORS	(0)	Not Required	(0)
1.1.1.3	SOLAR BLANKETS	12,027	Scaled from Reference	1,131
1.1.1.4	POWER DISTRIB.	2,250	Detailed Estimate	116
1.1.1.5	THERMAL CONTROL	(0)	Allocated to Subsystems	(0)
1.1.1.6	MAINTENANCE	427	Scaled from Reference	190
1.1.2	POWER TRANSMISSION	7,296		1,289
1.1.2.1	STRUCTURE	460	Scaled from Reference	38
1.1.2.2	TRANSMITTER SUBARRAYS	6,673.0	Detailed Estimate	1,097
1.1.2.3	POWER DISTR. & COND.	631.0	Scaled from 1.1.1.4	70
1.1.2.4	PHASE DISTR.	25	Scaled from Reference	51
1.1.2.5	MAINTENANCE	20	Docking Ports Only	20
1.1.2.6	ANTENNA MECH. POINTING	118	Scaled by Mass x Area	13
1.1.3	INFO MGMT & CONTROL	145	Scaled from Ref.	73
1.1.4	ATT. CONT. & STA. KP.	146	Scaled From Ref	110
1.1.5	COMMUNICATIONS	0.2	Same as Ref.	8
1.1.6	INTERFACE	113	Est. Based on Simplification	46.3
1.1.7	GROWTH & CONTINGY.	5,464	Same % as Reference	701

high-voltage systems because the latter require power processors and their associated thermal control.

A recurring cost estimate for the solid-state configuration is presented in Table 6. The cost per kilowatt is about 25% greater than for the reference system. As with mass, this arises mainly because of the low distribution voltage.

The cost trend chart, shown in Figure 9, was developed early in Phase II to compare solid-state "sandwich" configurations to the klystron reference systems. The antenna-mounted solid-state system is also spotted on the chart. It falls on the trend line. (Note that this chart uses 1977 dollars whereas other results in this report are in 1979 dollars.)

Laser Power Transmission

The laser power transmission study originally was intended to perform a quick screening of various laser option and then to select a reference system for additional definition. As the laser options were investigated, however, it became evident that this was not practical. Although a number of laser options are unsuitable for SPS application, several are, as summarized in Table 7. Those laser options showing the most promise were the least defined. Accordingly, it was necessary to invest substantial analytical effort in several promising laser options to compare their potential payoffs, as well as the relative uncertainty in their technology.

C... lectric discharge lasers are the ones about which the most is known. Lasers of this ... have been built and operated over a range of power levels. Both CO and CO_2 lasers were investigated. The CO lasers offers the highest efficiency of conversion of electric discharge power to laser light (approaching 50%), but have higher system losses, as well as less transmission efficiency because of water absorption of the CO lines in the Earth's atmosphere. The CO_2 laser offers as advantages those problems that are disadvantages to the CO laser. By selecting an isotope CO_2 laser, relatively good transmission efficiency can be expected on clear days or nights. The CO_2 gas in the lasing cavity can be operated at roughly room temperature rather than 60-80°K for the CO laser and, therefore, system losses due to refrigerating the lasant are much less.

SPS-3011 *Table 6 – 2.5 GW Solid State Satellite System Recurring Costs*

ITEM	COST ($M)
SATELLITE	3,722
LESS IMPLICIT AMORTIZATION	327
	3,395
CONSTRUCTION AND SUPPORT	664
SPACE TRANSPORTATION	2,154
GROUND TRANSPORTATION	[illegible]
RECTENNA	1,290
MISSION CONTROL	10
MGMT AND INTEGRATION	385
MASS GROWTH (17% Net Hardware)	577
TOTAL DIRECT OUTLAY	8,505

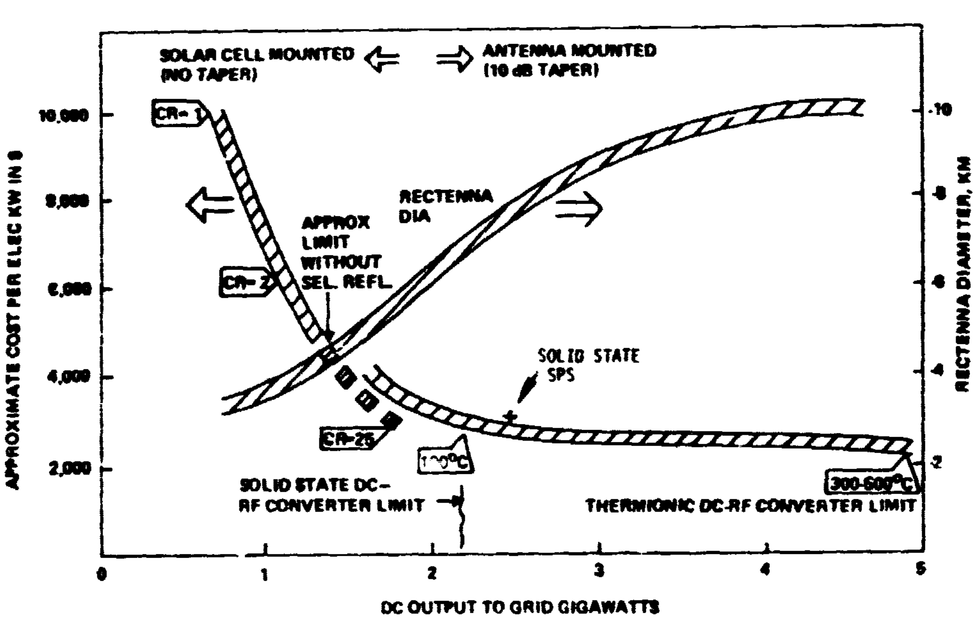

Figure 9 – SPS Cost Trends

Table 7—Laser Options First Screening

OPTION	SELECTED BECAUSE	REJECTED BECAUSE
GLASS OR RUBY LASERS		LOW EFFICIENCY; MASSIVE
CHEMICAL LASERS		NOT SUITED FOR STEADY-STATE OPERATION
EXCIMER LASERS		LOW EFFICIENCY
SOLID STATE LASERS		LOW POWER PER DEVICE; LOW VOLTAGE; COMPLEXITY
GAS DYNAMIC LASERS		LOW EFFICIENCY AND MASSIVE
GAS ELECTRIC DISCHARGE LASERS	POTENTIAL FOR HIGH POWER AND FAIR EFFICIENCY	
GAS OPTICALLY PUMPED LASERS	ELIMINATION OF SOLAR ARRAY	
FREE-ELECTRON LASER	POTENTIAL FOR HIGH POWER AND GOOD EFFICIENCY	

A comparative study concluded that the supersonic flow laser is the less massive than one using a conventional refrigeration cycle. Accordingly, the supersonic flow configuration was adopted.

The gas electric discharge lasers were estimated to be nearly ten times as massive as the reference microwave system.

It is possible to pump either a CO or a CO_2 laser directly with sunlight. Initial experiments have shown promising gain. This leads to the concept of the optically pumped laser using sunlight directly without conversion to electricity. A systems schematic and configuration concept are shown in Figure 10. The solar concentrator dwarfs the rest of the system. This laser option suffers from the same inefficiency and massive radiators as the electric discharge lasers. The solar collector, however, is very light; the total mass is less than that of the electric discharge gas lasers.

The optically pumped laser is complex to construct. This arises from the complexity of the configuration itself, especially the concentrator. Construction analysis by Grumman showed a construction productivity only about 1/50 (megawatts per crewperson—year) of that for the microwave SPS.

The free electron laser extracts coherent light from a high energy electron beam. This is somewhat analogous to the extraction of RF energy from an electron beam by the Klystron microwave amplifier. The efficiency limitations associated with gas lasers are avoided; it is possible that conversion of electron beam power to laser light may be efficient. Two possibilities exist for a highly efficient free electron laser: (1) It may prove feasible to design a wiggler magnet* which has high gain as well as efficient extraction of light energy from the electron beam. (2) A circulating beam might allow a high-gain, low extraction wiggler magnet to extract most of the electron energy by causing the electrons to make many passes through the magnet. In either case, the free electron laser SPS is a solar array driving an electron beam accelerator which in turn drives the laser to produce light. A conceptual FEL SPS configuration is illustrated in Figure 11.

* This is the device that converts electron beam energy to optical energy.

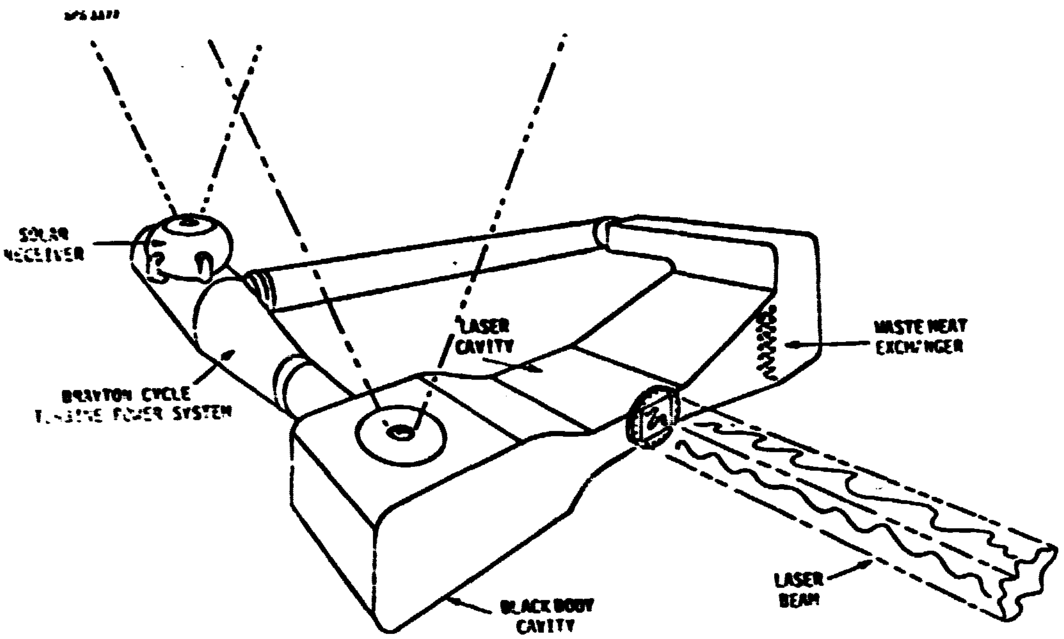

Figure 10 – Optically-Pumped Laser Concept

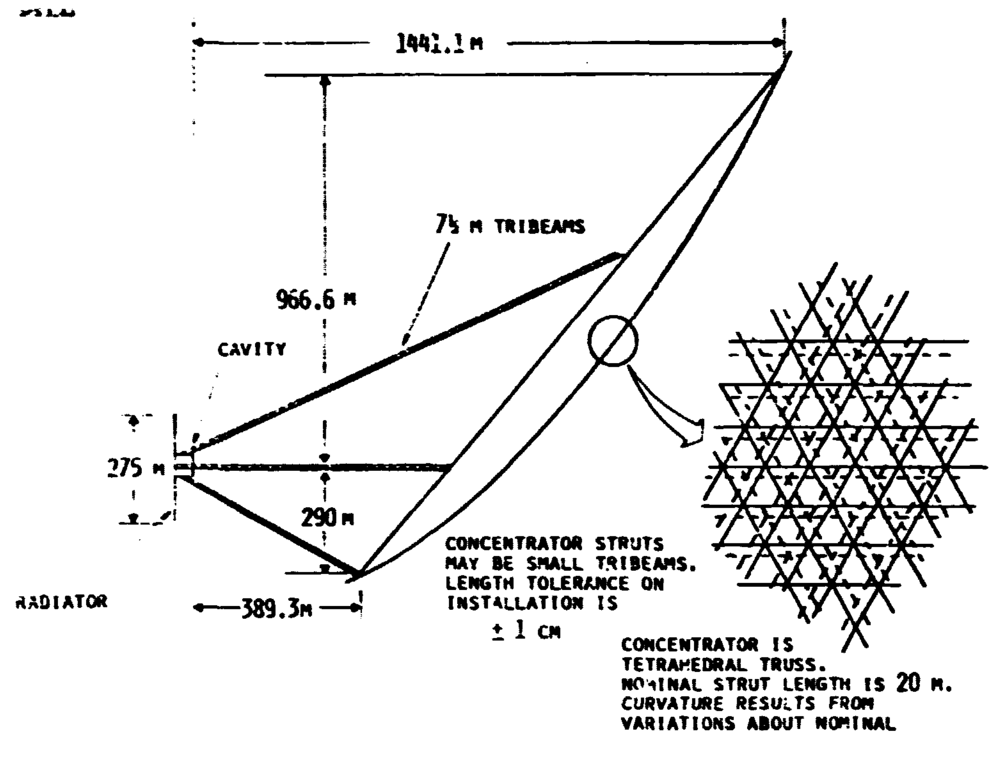

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Figure 10—Optically-Pumped Laser Concept (Continued)

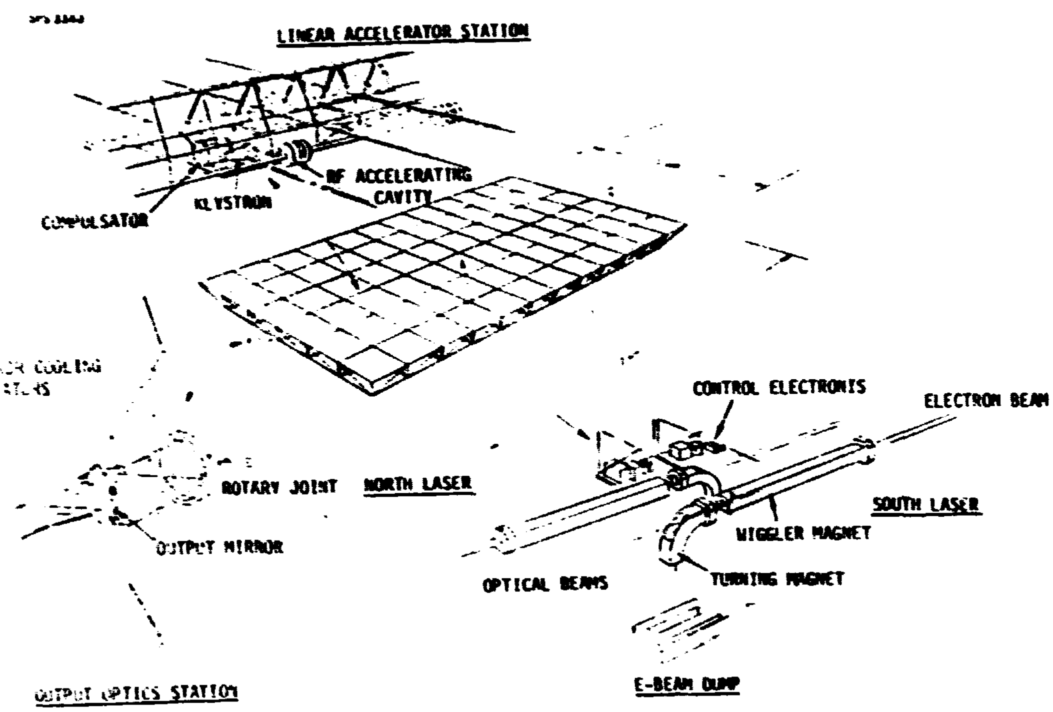

Figure 11—Free Electron Laser SPS Concept

Heavy-Lift Launch Vehicle (HLLV) Alternatives

The SPS Systems Definition Studies initially selected a large ballistic sea-landing HLLV. A subsequent tradeoff led to a performance of a two-stage winged HLLV. Both the flyback booster and the orbiter are to return to the launch site for reuse. This reference vehicle has an estimated gross payload of 420 tonnes and a gross liftoff mass of nearly 11,000 tonnes. Its payload bay is 17 mmeters in diameter by 23 meters length.

The estimated costs of development and acquisition of fleet and facilities for this vehicle is the largest single item in the estimated reconcurring cost of the SPS program. Further, the vehicle is so large that alternative uses are not presently foreseen. For these reasons, Phase III of the present study investigated alternatives to the reference HLLV. One was a means of using Shuttle hardware (with a new booster) for SPS transportation, orbit-to-orbit as well as launch. The other was a smaller HLLV much like the reference HLLV in design concept. In this latter case, other elements of the SPS reference system were to be altered only as dictated by the smaller payload bay and lift capability.

The concept of the shuttle-derived system centered around use of a large booster to increase the gross injected mass of the orbiter, external tank, and payload, thus increasing payload substantially. On cargo flights, a modified ET would be used, one with a payload bay in the nose. Additional cargo could be carried in the orbiter payload bay. Some of these cargo ET's would also be fitted for orbit-to-orbit operations. Additional modifications include head-to-tail docking and propellant delivery fixtures and better propellant thermal insulation to allow up to two weeks of orbital operations. The oribit-to-orbit configuration consists of several ET's docked together head-to-tail. An orbiter joined to the tail-end ET would provide propulsion, flight control and personnel accommodations. After delivering personnel and cargo to GEO, the oribter with one ET would return propulsively to Earth orbit.

The orbit-to-orbit assembly would be tanked by propellant delivery shuttle flights from Earth. Without payload, these flights would arrive at low Earth orbit with about as much residual propellant as the payload lift capability. Most of this propellant would be transferable to the orbit-to-orbit assembly. The ET's would be fitted with suitable docking and propellant transfer equipment.

Analysis of this concept reached several conclusions:

1) Because of the fixed cost per flight for ET's and orbiter operations, the system optimizes for recurring costs with large boosters and payload per launch in the 250-300 tonne range. The booster size approaches that for the large reference HLLV.

2) The recurring cost per SPS is estimated as roughly twice that of the reference transportation system. A parametric cost estimate considering variations in booster size and numbers of ET's per orbit transfer flight is shown in Figure 12. A large part of this higher cost derives from the comparatively inefficient chemical orbit-to-orbit system. Compared to the reference electric OTV cargo system, nearly twice as much mass must be delivered to low Earth orbit.

3) The development and other nonrecurring costs are less than for the reference HLLV but comparable to those for the small HLLV. Although development needs are less than for the small HLLV system (the shuttle derived system also replaces the EOTV and personnel orbit-to-orbit systems, these elements must be included in the cost trade), the greater flight rate increases fleet and facility acquisition costs.

A second approach to reduction of SPS nonrecurring costs is the selection of a smaller HLLV. Size selection for the HLLV must evaluate two primary factors: (1) variation in performance, e.g., payload-to-liftoff mass ratio, with size, and (2) effects in other elements of the SPS program deriving from the smaller payload bay volume and lift capability.

Investigation of SPS hardware packaging requirements led to selection of a payload bay volume of 11 meters square by 14 meters in length. This is sufficient to accommodate transmitter subarrays fully assembled, but requires redesign of solar array attachment. The electrical slip ring assembly, the personnel orbit transfer vehicle, and space base crew habitats. The stated redesigns were required to achieve any meaningful reduction in payload bay volume. Subarray final assembly on orbit was considered to be an undesirable added space construction workload.

Parametric investigations indicated a payload lift capability of 120 tonnes to be appropriate, and indicated this to be achievable with 4000 tonnes liftoff mass. More lift capability could not be used effectively because of SPS hardware packaged volumes; less

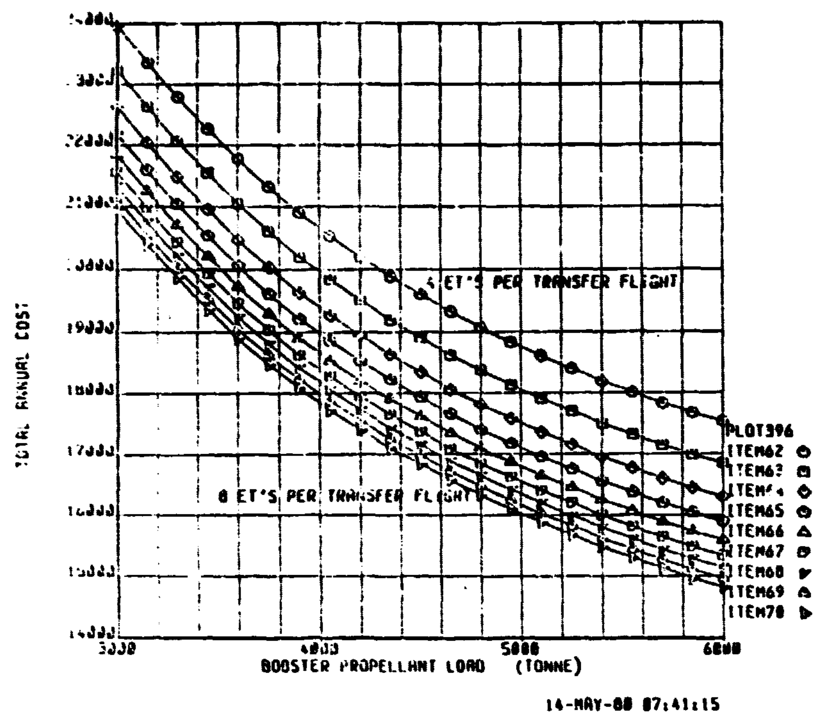

Figure 12—Total Annual Cost for Shuttle-Derived Transportation System

resulted in rapid degradation of performance as shown in Figure 13. The resulting vehicle is compared in size to the shuttle, the Saturn V and the SPS reference HLLV in Figure 14.

Performance and mass properties analyses indicated a gross lift capability of 125 tonnes. Cost analyses estimated that the smaller vehicle would result in a three percent increase in total recurring cost per SPS and save at least five billion dollars in nonrecurring cost. Results are summarized in Table 8. Additional benefits were seen in reduced sonic overpressure and launch noise as well as in facilities costs.

The nonrecurring financial risk reduction is considerably greater than the five billion dollars noted. The savings during development are greater than this but are partially offset by higher investment costs for the fleet and for the construction bases. Further, the small HLLV is of an appropriate size and capability for alternate mission uses after 1990; its development does not appear to be an SPS-unique requirement.

For the reasons stated, it is recommended that the small HLLV be adopted as the SPS reference HLLV for future studies.

Space Construction

During Phase I, Grumman and Boeing jointly examined a number of construction approaches, the most important illustrated in Figure 15. **The four-bay end-builder was selected as a result of this tradeoff, based on its productivity potential.**

During Phase II, Grumman conducted a definition effort on the geosynchronous orbit (main) construction base. **The results provide a thorough understanding of SPS construction and an adequate basis for space worker health and safety assessments.** Additional definition of the LEO (staging and electric orbit transfer vehicle construction) base was provided by Boeing. An example of GEO base definition is shown in Figure 16, an illustration of the final stages of yoke/rotary joint construction.

In the first view, the yoke is shown complete positioned ready to receive the antenna. The construction facility is positioned to the left to complete fabrication of the remaining yoke sections.

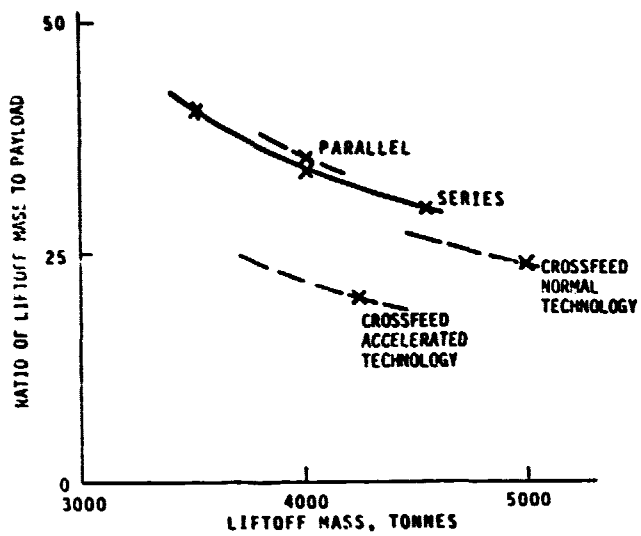

Figure 13—HLLV Performance Mass Trending

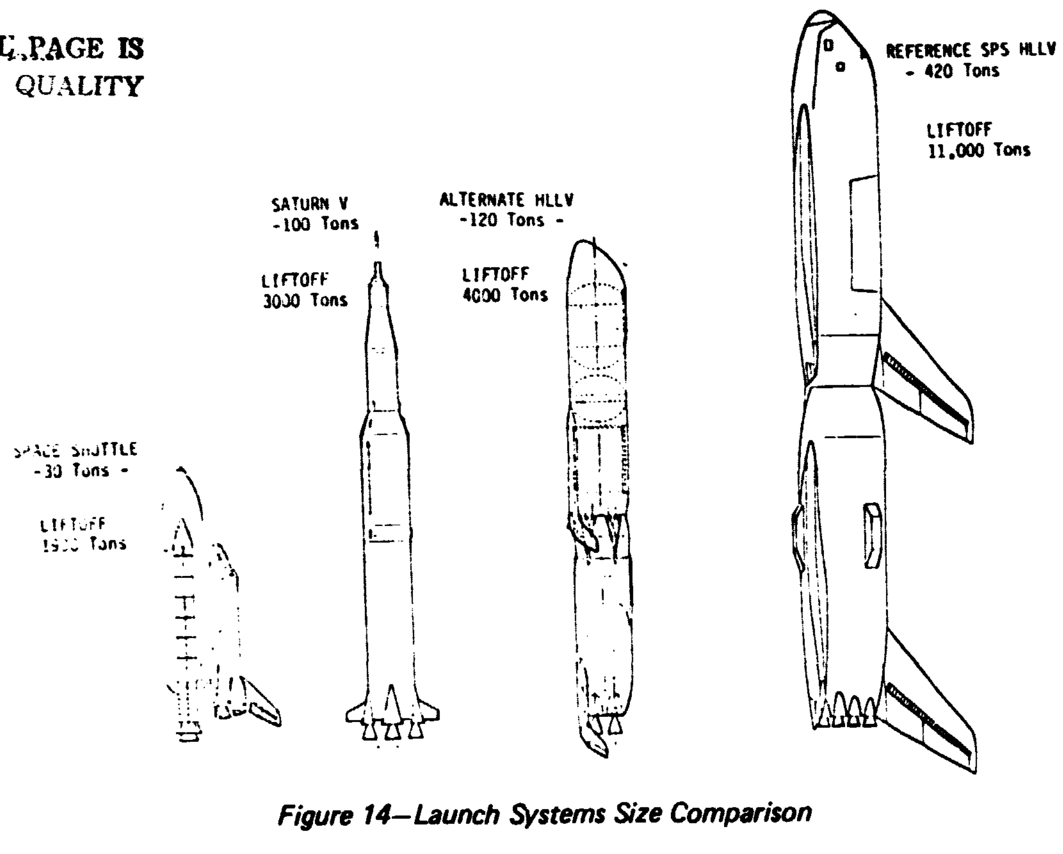

Figure 14—Launch Systems Size Comparison

Table 8—Delta Cost Summary for Small HLLV

SPS 3433

	NONRECURRING	RECURRING SPS	RECURRING TRANSPORTATION	RECURRING CONSTRUCTION
SATELLITE DESIGN CHANGES	230 (BASE CHANGES)	16.3	90.4	4.12
CARGO LOGISTICS	250.1	—	—	5.2
SMALLER CREW MODULES		—	—	132.1
DDT&E	-2521 [1]			
INVESTMENT	3925 + 34.4			
TRANSPORTATION		—	1040 (HLLV) -400 (PLV)	—
DDT&E	-3075			
FACILITIES INVESTMENT	-3049			
FLEET INVESTMENT	790 [2]			
HLLV FACTORY	1619			
LESS SHUTTLE MODS	-3204			
TOTAL	-5000.6	16.3	730.4	141.42
		TOTAL = 887		

[1] INCLUDES CREDIT FROM DEMONSTRATION PHASE

[2] TOOLING UNDERESTIMATED FOR LARGE HLLV?

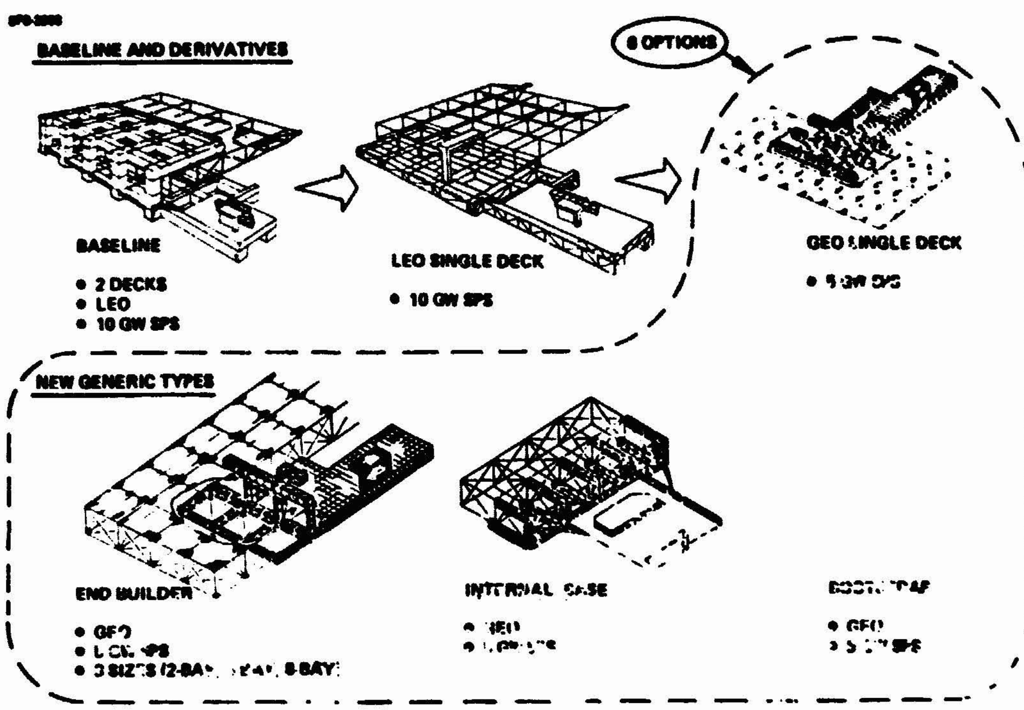

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Figure 15 – Alternative Construction Concepts

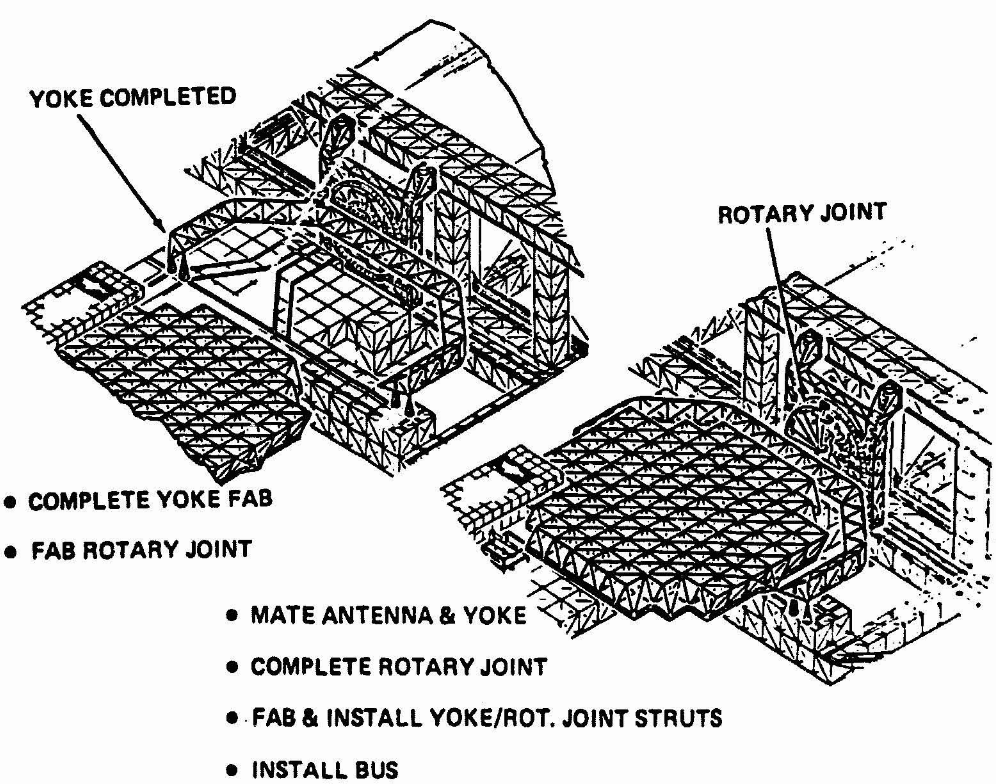

Figure 16 – Yoke/Rotary Joint Assembly

In the second view of Figure 16, the antenna and yoke have been mated and the yoke, supported entirely by the indexer supports has been separated from the construction facility. The facility is now free to begin fabrication of the rotary joint.

This definition effort led to an update of space construction base costs, masses, and crew complement requirements. These updates are reflected in the system costs presented earlier.

Construction Analyses for Alternative Systems

During Phase III, Grumman analyzed the construction aspects of the alternative systems discussed above. Construction base designs were developed for the solid-state and laser SPS options. Necessary modifications to the reference construction base to adapt to the small HLLV were also defined. The solid-state construction base was very similar in general appearance to the reference base. Its antenna construction facility was modified to better adapt to the larger solid-state antenna. The reference system indexes (moves) the antenna past a fixed work area, but it was found that the size and mass of the antenna construction facility for the larger 1.4 km solid-state antenna could be reduced by indexing both the antenna and the work area. An additional change reflects the change in antenna attachment from a yoke mount in the reference case to an edge mount in the solid-state configuration. This change simplifies array-to-antenna assembly operations and should be considered for the reference SPS. The array assembly facility is little changed from the reference system.

The laser configuration investigated was the indirectly optically-pumped laser. The other laser options are similar in general arrangement to the reference SPS but smaller. Extrapolations from prior and concurrent construction studies for other planar configurations were used to develop preliminary estimates of construction requirements for these. The IC̄ L option represents a radical configuration departure from the reference concepts and merited a special analysis to assess construction problems. The configuration wa similar in general arrangement to thermal engine SPS's and posed similar problems.

The construction base configuration developed by Grumman for this laser option is illustrated in Figure 17 with the laser SPS shown attached to the base, nearing completion. Also summarized in the figure are the relative performance indexes for the

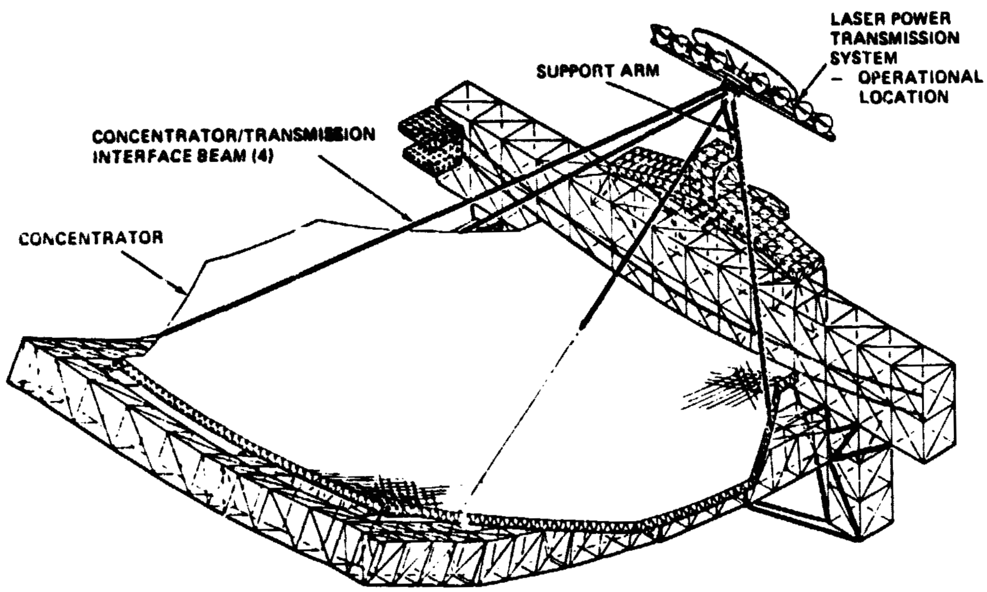

Figure 17–Laser SPS-Final Systems Mating

reference, solid-state, and IOPL laser bases. The productivity of the laser base is so low that unless a much more streamlined approach to construction is found, the IOPL should be dropped from further consideration. Productivity of the bases for the other laser options was estimated to be within roughly a factor of two of the reference SPS construction base. The productivity of the solid-state base is about 78% of the reference. The loss in productivity stems mainly from the four times greater antenna area per megawatt that must be constructed.

Rectenna Construction

General Electric defined a mechanization and structural concept that reduces rectenna costs from earlier estimates. A pictorial summary of the construction concept is illustrated in Figure 18. The basic support structure is steel-reinforced concrete. This support structure is emplaced by construction equipment employing advanced technology location systems to allow precise location of the footings. Support and rectenna panels are manufactured at the site in portable factory buildings and moved for installation as illustrated. The resulting total rectenna cost, including the rectenna-power pool interface equipment, is $2578 millions in 1979 dollars; this figure is reflected in the costs reported in Table 4.

Concurrently with the Phase II effort, Boeing developed a concept for using rectenna structures as a basis for large-scale controlled-environment agriculture (i.e. a greenhouse). This appears quite feasible and would ameliorate concerns regarding the land use associated with rectenna sites.

SPS Maintenance

Maintenance analyses concluded that maintenance costs would be roughly 0.3¢/kwh and that failed hardware should be refurbished at the GEO Base to the extent practicable. Analyses of the maintenance systems established means of maintenance access for all system components and estimated actual crew counts both for remove/replace options and for equipment repair operations at the geosynchronous base. Additional definition of installation specifics was required in order to accomplish the maintenance analysis. Illustrated in Figure 19 is a representative access concept for gaining access to power buses and switchgear. The multiple bus power distribution system is accessed by a flying cherrypicker which is a part of the maintenance system.

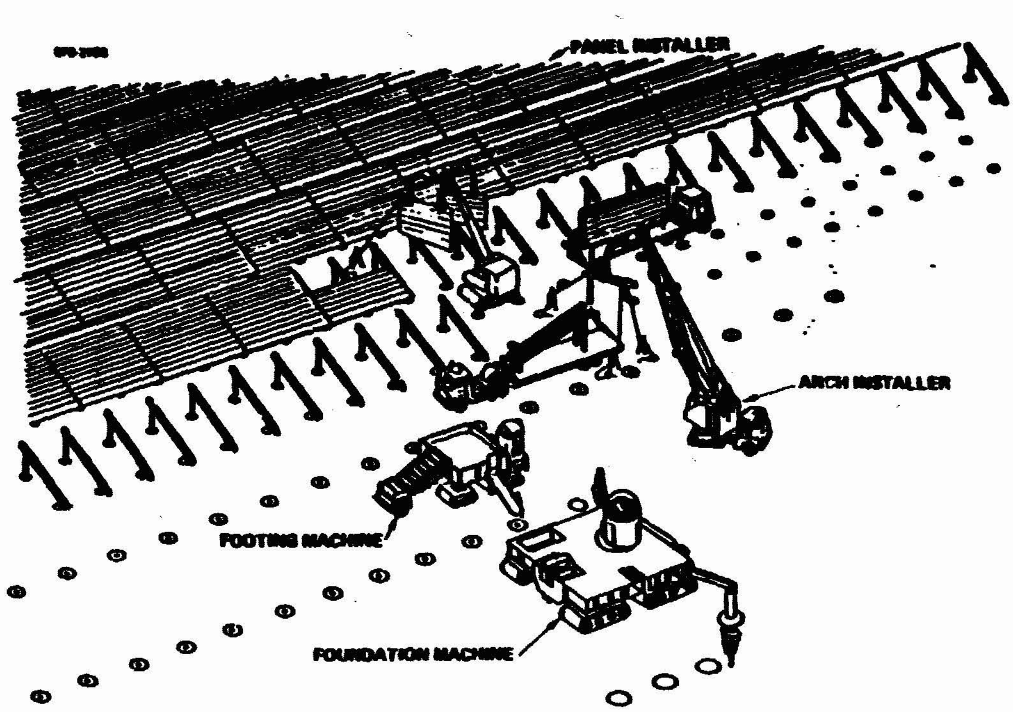

Figure 18 – Five GW Rectenna Construction Concept

Table 4 – Ground Receiving Station Cost Summary

		Cost Million of $
Land	47,800 acres	120
Structures & Installation		346
RF Assemblies & Ground Plane		959
Distribution Busses		308
Command & Control Center		70
Power Processing & Grid Interface		775
		2578

These figures are for one receiving site.

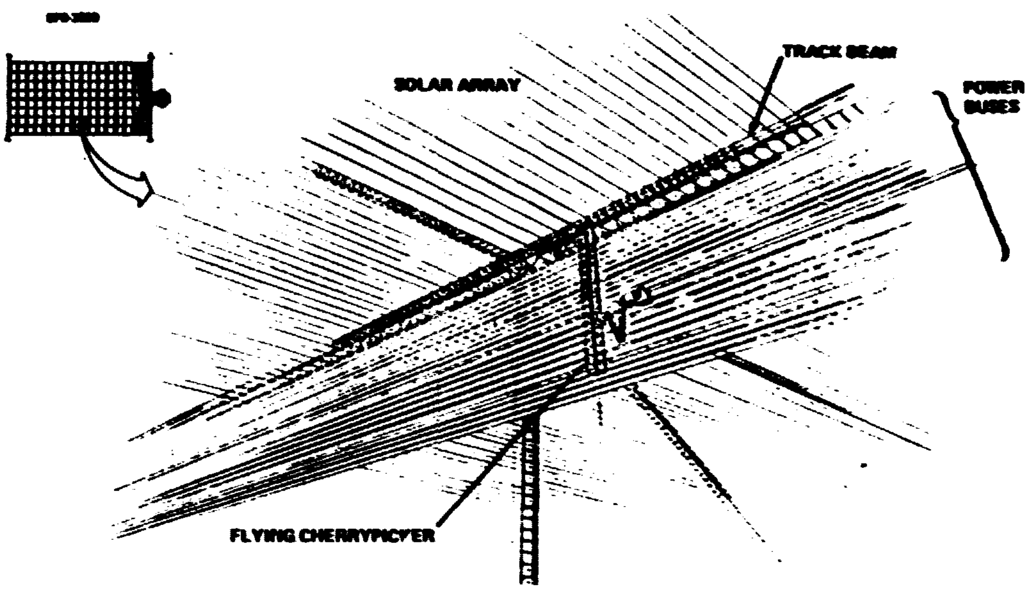

Figure 19 — Main Bus Maintenance Access System

Based on these maintenance access concepts, a complete operations concept was developed. Hardware repair tasks at the GEO base were timelined and manloaded, and overall maintenance costs were estimated.

Table 9 summarizes the results of the maintenance analysis and indicates the estimated cost of satellite maintenance to be approximately 0.3 cent per kilowatt hour. This cost did not include rectenna maintenance. Costs of maintenance of space vehicles and bases were included in operating costs for those systems. This cost is categorized in utility language as "operations and maintenance cost." In order to develop the maintenance estimate, a timeslice was taken with 40 SPS's in orbit. This maintenance estimate assumes that each SPS is serviced every six months.

INDUSTRIAL INFRASTRUCTURE NEEDS

Solar array production facilities were identified as the only major challenge in developing the SPS industrial infrastructure.

The ground-based industrial infrastructure required for SPS hardware production was scoped by Arthur D. Little. Investment cost estimates in Table 10 are rough order-of-magnitude. (Most of these investments would be absorbed by the private sector.)

The estimates for solar array production are "upper bound" figures assuming only very moderate technological advance (but extensive automation) compared to today's methods. The figures in Table 10 exclude space transportation vehicle launch and recovery facilities and propellant production facilities, described below. Existing ground transportation methods and facilities were found to be adequate.

Propellant production requirements to sustain SPS production at 10,000 megawatts per year are summarized in Table 11. Plant capital cost and energy requirements were derived from a Boeing Commercial Airplane Company study of synthetic fuels for commercial aircraft.

The energy investment in propellants is small. If the electricity requirement is met by coal-fired generation, the total coal consumption approximately doubles. Stated another way, 25,000 tons/day of coal for one year can generate, if used directly, about 2,000 megawatt-years of electricity. Used to produce SPS rocket propellant, the same quantity of coal contributes the transportation energy to generate 300,000 megawatt-years of electricity.

Table 9 — Maintenance Cost Summary: 40 SPS

ITEM	NUMBER	COST ($M79)	REMARKS
HLLV	80 Flights	936	
PLV	38 "	460	
EOTV	5 "	226	
POTV	36 "	88	
TOTAL TRANSPORTATION OPS		1710	
MAINTENANCE CREW	650	1785	Assumes 10 support people on ground per space worker
SPARES		800	
MISSION CONTROL		20	
TOTAL ANNUAL COST		4315	23rd year of production program

$$\text{O\&M COST} = \frac{4315 \times 10^6}{5 \times 10^6 \text{ KWH} \times 8766 \text{ HR/Y} \times 0.9 \text{ Plant Factor} \times 40 \text{ SPS's}} = 0.27 ¢/\text{KWH}$$

Table 10 — Industrial Infrastructure Summary SPS Hardware Production

ITEM	CURRENT CAPACITY	SPS CAPACITY REQUIRED	INVESTMENT COST ($M79)	REMARKS
Solar Array	≈1 MW/YR	18,000 MW/YR	5000	Photovoltaics consume only about 5% of current semiconductor silicon production
Ion Thrusters	Nil	5000 to 10000 units per year	None	Can be absorbed by existing infrastructure
Klystrons	7000/yr	200,000/YR	1500	Present magnetron production is ≈ 2 GW/YR
Rectenna	N/A	2 rectennas/yr	250	Materials consumption small compared to existing productive capacity
Graphite Fibers	150 T/Yr	≈10,000 T/YR	549	About twice projected U.S. capacity in 1993.
Other			1625	Mostly electronics
TOTAL			8924	

Table 11– Propellant Production Requirements SPS Construction at 10,000 Megawatts/Yr.

	METRIC TONS/YR				TOTAL [1]	PLANT CAPITAL	
	HLLV	POTV	EOTV	PLV	TONS/DAY	COST $M79	
LO_2	2,671,000	3,722	1,060	57,700	9,000 [2]	650	From Coal [6] and Air
LCH_4	642,600	-0-	-0-	18,700	2,200 [3]	615	
LH_2	123,704	745	353	3,036	420 [4]	500	
ARGON	-0-	-0-	14,400	-0-	47 [5]	-0-	

[1] Capacity required at start of program; includes 20% margin

[2] 1979 U.S. capacity is about 30,000 tons/day

[3] About 0.2% of U.S. Natural Gas Consumption in 1977

[4] Today's capacity is ≈ 100 T/Day

[5] Byproduct of LO_2 Plant

[6] 12,250 T/D coal + 1000 megawatts electric power. Coal use is 0.7% of U.S.'77

LAUNCH SITE ANALYSES

Facility Requirements

Preliminary definitions of launch and recovery facility requirements were developed in Phase I for the reference transportation system and in Phase III for the small HLLV. A major difference is that the reference system requires offshore pads whereas the small HLLV does not. Facility general arrangements are compared in Figure 20. **The result was an estimated total facilities cost of 5.11 billion dollars for the reference system compared to 1.8 billion dollars for the small HLLV.** This savings was one of the most important contributors to reduced nonrecurring cost for the smaller vehicle.

The launch site location analysis task was motivated by the premise that selection of a low-latitude site would offer significant cost advantages compared to operations from the Kennedy Space Center, where earth-to-low-orbit space transportation arrives at a 30° inclination orbit. With a 30° inclination orbit for staging or construction operations, a 30° plane change is required to reach a geosynchronous equatorial orbit. It was presumed that this plane change would incur significant performance penalties relative to a zero-degree or low-inclination low earth orbit. However, **with electric propulsion, the performance difference is minimal.** (It should be recognized that a significant delta V advantage for equatorial launch exists for chemical orbit transfer to GEO.) The principal motivation for leaving KSC for a remote site will stem from the eventuality of SPS operations outgrowing KSC. Our estimates to date indicate that KSC can handle approximately 10 gigawatts per year of SPS construction.

As a part of Phase II, Brown & Root developed the concepts shown in Figure 21 for structural support of an offshore launch facility in water depths up to 200 m (650 ft). The facility would include launch and recovery facilities, the latter requiring a 91 x 4572 m (300' x 15,000') runway which dominates support structure costs. The facility would be located off the west coast of South America, roughly 325 km north of the Galapagos Islands. At that location, weather and sea states are unusually mild (the "doldrums").

Since the offshore approach would allow most of the launch and recovery equipment to be installed on the support structure sections as they are built in a shipyard (rather than constructed at a remote site), the savings in equipmen. installation and checkout and site

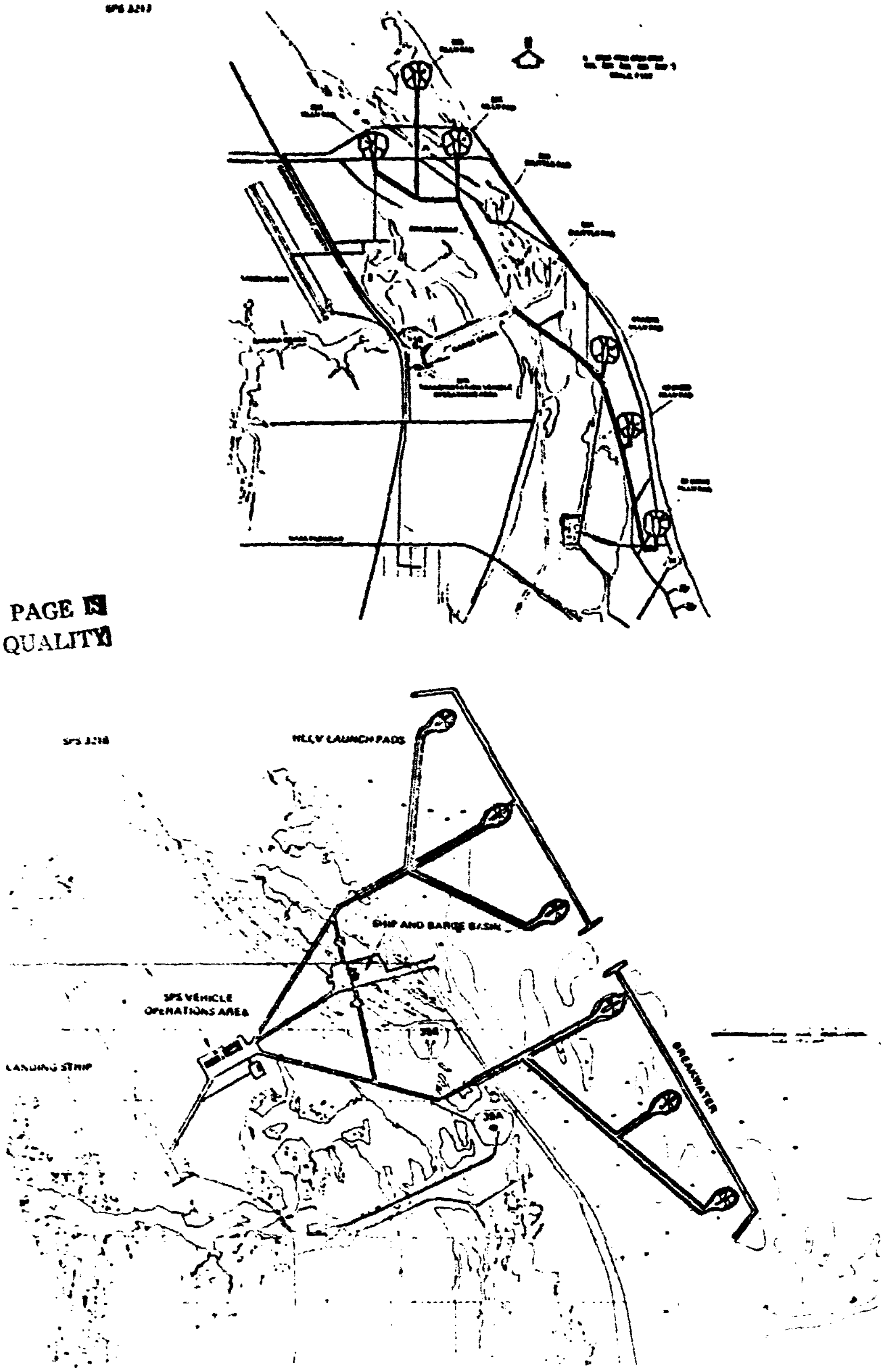

Figure 20—Launch Facilities Requirements Comparison
SPS Launch and Recovery Site for a Small HLLV

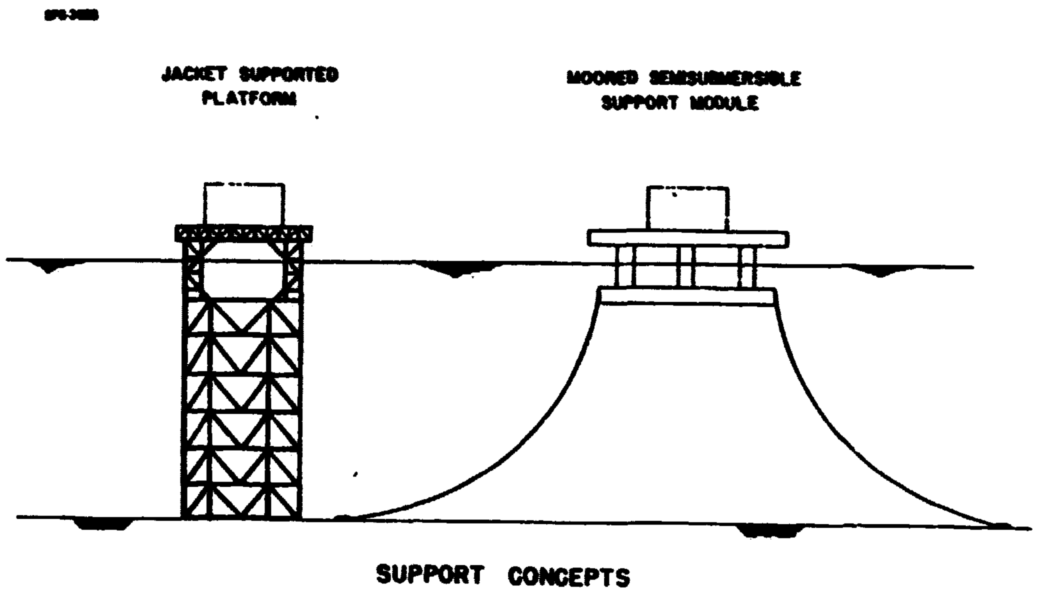

Figure 21 – Brown and Root Offshore Launch Design Concepts

preparation could more than offset the cost of offshore structures. The major conclusions of the Brown & Root study were as follows:

- It is technically feasible
- Conceptual design to completion will require only six years
- Total installed cost estimates were: (1) moored, semi-submersible-$3,005,000,000; (2) stationary, pile-supported-$3,917,000,000
- The runway is a significant cost driver
- The concept has real benefits
- It is probably the least cost way to provide a large equatorial launch complex

OPERATIONS ANALYSES

Launch Trajectories

Depressed launch trajectories were found that will mitigate the environmental concerns relating to the possibility of influences on the upper atmosphere from launch operations. Figure 22 shows the relationship of the current baseline trajectory to the key regions of the upper atmosphere.

Some forecasts of ionosphere depletion due to SPS launches have assumed the HLLV trajectory would be like the Skylab trajectory shown, which thrusted directly into the ionosphere F-layer. The reference HLLV trajectory does not enter the F-layer under mainstage thrust; only the circularization and de-orbit burns occur at that altitude. This reduces the concern about ionosphere depletion by about a factor of five as compared to direct ascent into the ionosphere. Concern still exists because of the potential of hydrogen diffusion upward into the ionosphere. If the trajectory could be suppressed to stay below 100 km (328,000 feet), this concern would be greatly alleviated.

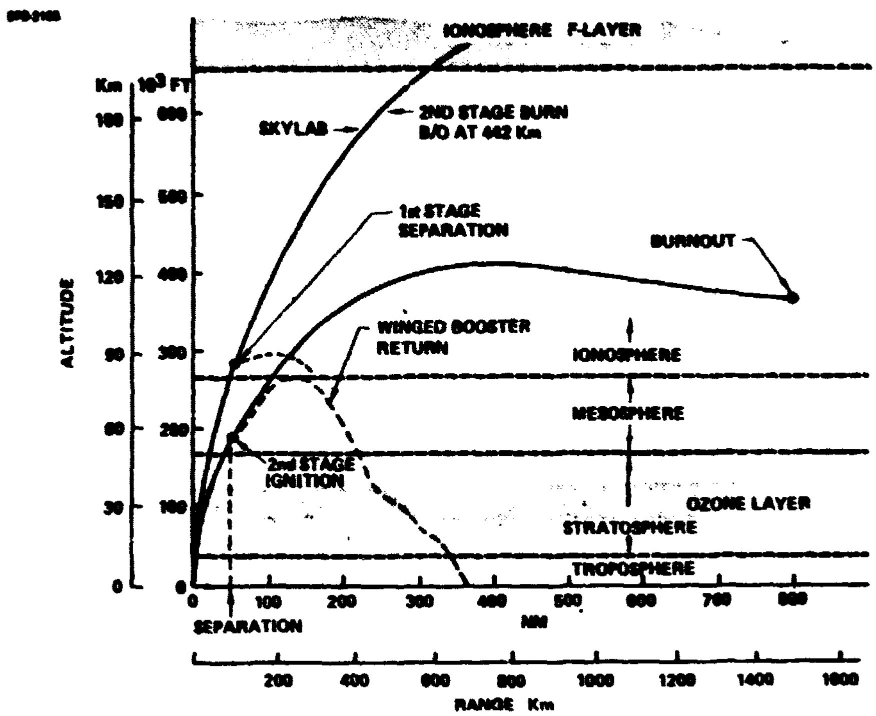

Figure 22 – Reference HLLV Launch Trajectory and Skylab Launch

An initial depressed trajectory was developed during Phase I of the study. It is low enough to keep the rocket effluents in the turbulent mixing regions of the atmosphere, reducing concerns regarding hydrogen diffusion.

During Phase II, a further concern was expressed that the trajectory developed during Phase I may not be depressed enough. The issue was possible formation of noctilucent clouds (due to H_2O) at about 80 kilometers altitude. It was desired to find a trajectory that would stay below 75 km.

Injecting the orbiter at a slight positive (e.g., 2^o) path angle has a significant beneficial effect on a highly depressed trajectory: (1) it minimizes post-injection drag losses; (2) it suppresses the pre-injection optimal path: (3) it forces an angle of attack on the orbiter similar to that for entry so that special thermal protection should not be required.

The selected 75-km-or-less trajectory is shown in Figure 23.

Results from 25 ascent trajectory simulations are summarized in Figure 24. It was found that the best trajectories had a peak ascent altitude of about 110 kilometers. Trajectories could be suppressed to keep the path below 100 kilometers with a slight performance penalty. Suppression to 75 km incurs about a 10% penalty.

The suppressed trajectories were not fully optimized and no credit was taken for the reduced booster flyback range. Ultimate penalties will be slightly less than indicated.

OPERATIONS

Operational Comparisons

Overall operations for the alternative SPS's were characterized. Figures 25 and 26 summarize the operations comparison. Most striking is the extreme penalty on space construction imposed by the optically-pumped laser option. These comparisons were drawn for a fixed 10,000 megawatts per year annual installation rate.

Integrated SPS operations were analyzed and plans prepared for each of the twelve operations arenas noted in Figure 27. One of the main outputs of these analyses was the communications requirements matrix shown in Figure 28. (Numbers in the matrix refer to

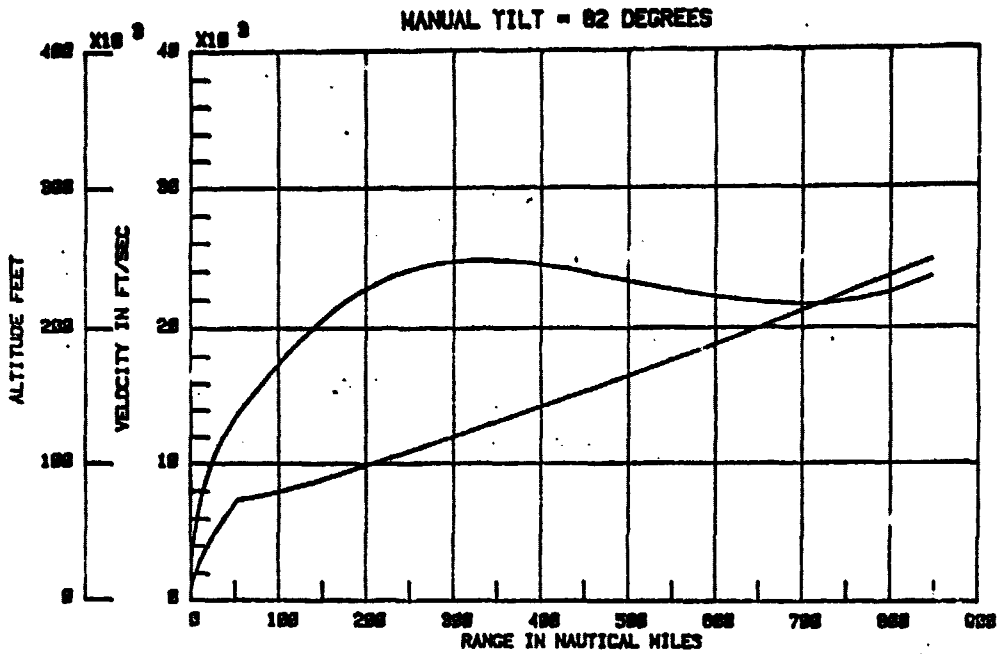

Figure 23 – HLLV Suppressed No. 6

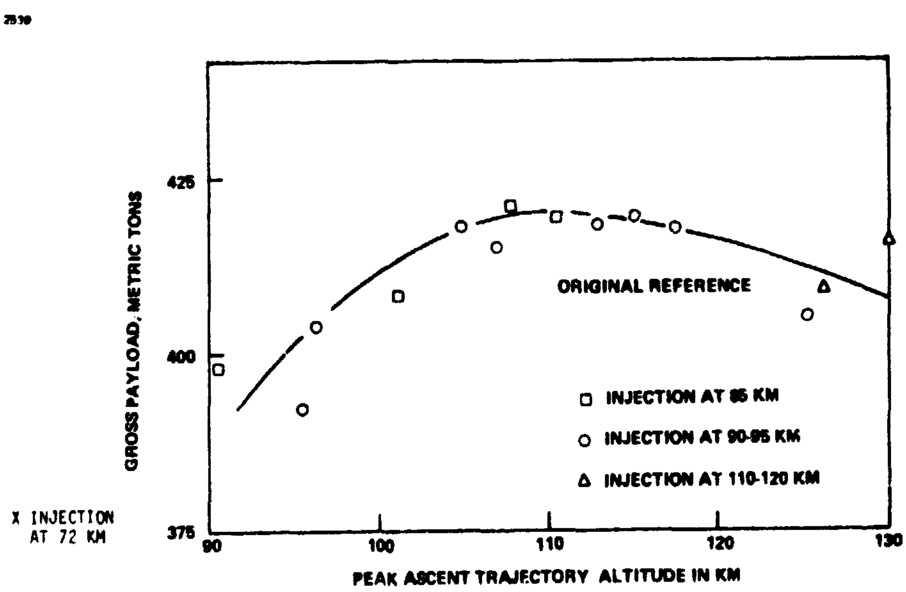

Figure 24 – Launch Trajectory Suppression Results

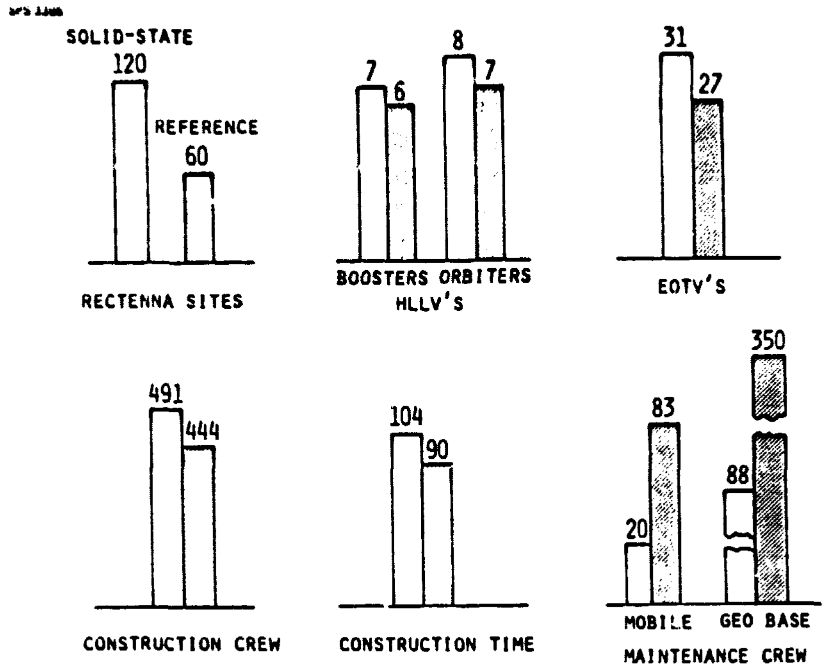

Figure 25—Operations Comparison: Solid State and Reference

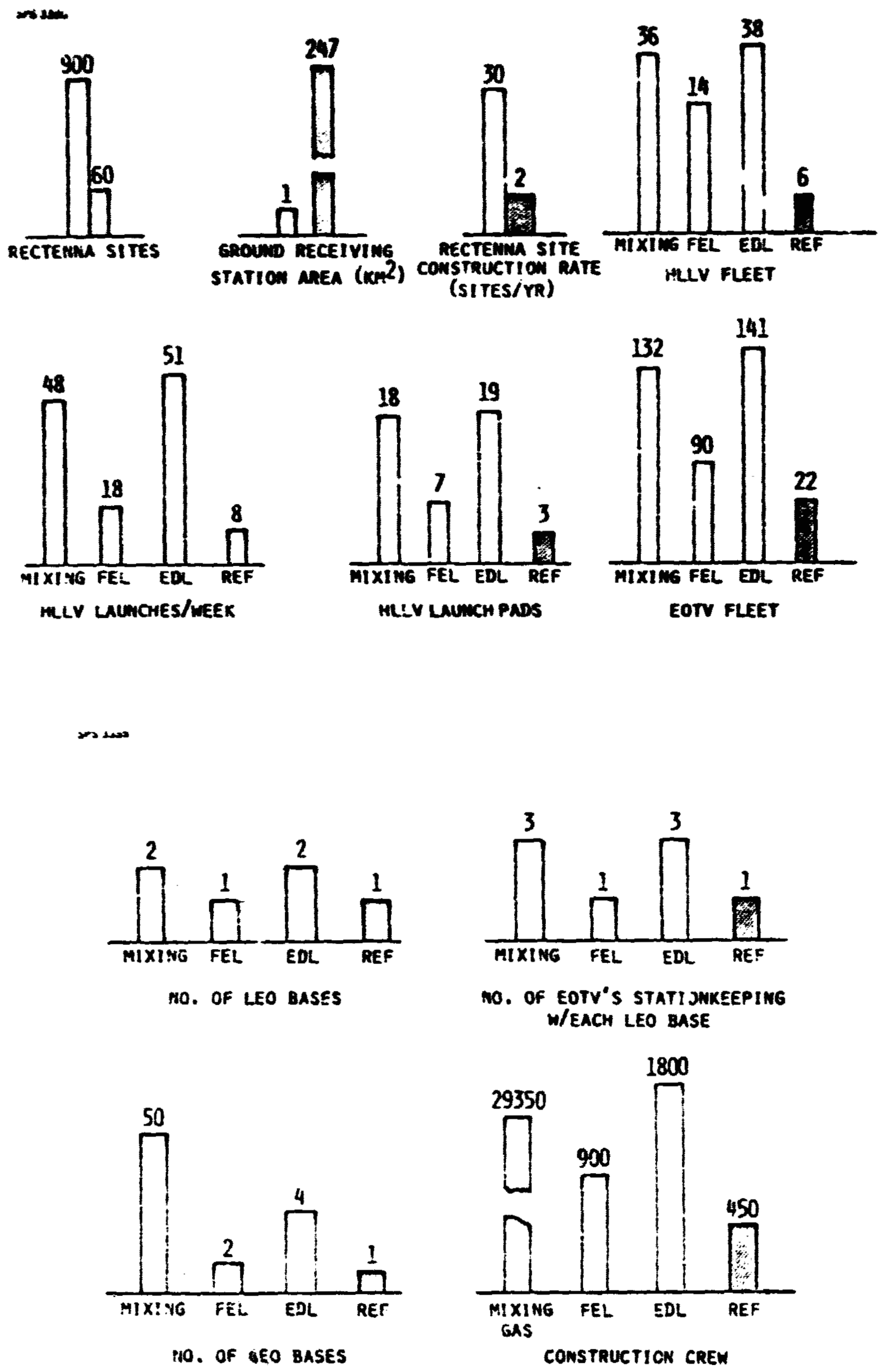

Figure 26—Laser SPS Operational Factors

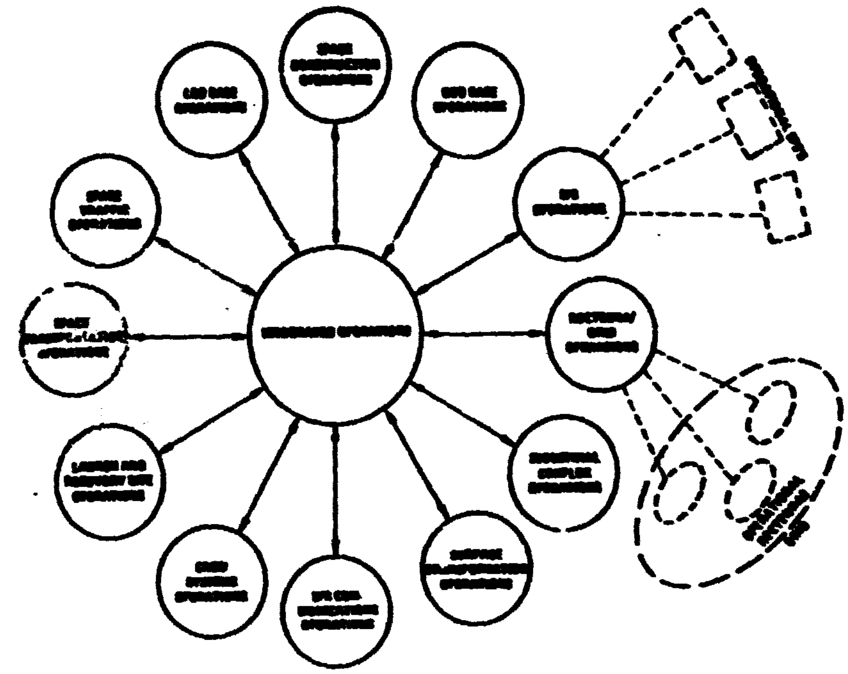

Figure 27 — Integrated Operations Concept

	OCC	LCC	LEO BASE	GEO BASE	MMB	SPS's	RCC	PLV	HLLV	EOTV	POTV	CARGO TUG	MSS-OTV
OPERATIONS CONTROL CENTER (OCC) (WBS 1.5.1)	X	1	2	3	4	5	6	7	8	9	10	X	11
LAUNCH CONTROL CENTER (LCC) (WBS 1.3.7.5)		X	12	X	X	X	X	13	14	X	X	X	X
LEO BASE (WBS 1.2.2)			X	15	X	X	X	16	17	18	19	20	X
GEO BASE (WBS 1.2.1)				X	21	22	X	X	X	23	24	25	26
MOBILE MAINTENANCE BASE (MMB) (WBS 1.2.3.2)					X	27	X	X	X	X	X	X	28
SOLAR POWER SATELLITES (SPS's) (WBS 1.1)						X	29	X	X	X	X	X	X
RECTENNA CONTROL CENTER (RCC) (WBS 1.4.6)							X	X	X	X	X	X	X
PERSONNEL LAUNCH VEHICLE (PLV) (WBS 1.3.3)								X	30	X	31	32	X
HEAVY LIFT LAUNCH VEHICLE (HLLV) (WBS 1.3.1)									X	X	33	34	X
ELECTRIC ORBIT TRANSFER VEHICLE (EOTV) (WBS 1.3.2)										X	X	35	X
PERSONNEL ORBIT TRANSFER VEHICLE (POTV) (WBS 1.3.4)											X	36	X
CARGO TUG (WBS 1.3.6)												X	37
MAINTENANCE SORTIE SUPPLY OTV (MSS-OTV) (WBS 1.3.3)													X

NUMBERS ARE FACT SHEET NUMBERS
X SIGNIFIES COMMUNICATIONS NOT REQUIRED

Figure 28 — SPS Communications Matrix

communications requirements fact sheets included in the detailed operations report, Volume III.) **A significant conclusion was reached: operations management will not be a significant contributor to SPS costs.**

Rectenna/Power Pool Compatibility

During Phase I, an investigation of rectenna siting was carried out. The analysis concentrated on the three areas shown in Figure 29, and examined site selection using detailed maps of the areas. **Enough siting opportunities were found to more than satisfy the expected needs of these utility regions for baseload power.**

Some investigators have expressed a viewpoint that SPS receivers can only be sited south of 35°N latitude. This apparently arises from a concern over having the incoming power beam nearly parallel to Earth's magnetic field lines. It is possible that this parallel situation could exacerbate ionosphere heating by the beam. If this turns out to be a real problem, it can be alleviated by a longitude offset between the SPS and its ground receiver. **We have not found reason to restrict rectenna siting to a 35° latitude limit.** It is true, of course, that greater land area is required further north, but the rectenna panel area (the main cost contributor) changes little.

Available SPS power to utility networks was estimated, considering random errors, failure modes, scheduled maintenance and eclipse, including shut down and start up times. System planned total outage (down time) is 207.8 hours per year (2.37%).

The description of the rectenna-to-power grid connection approach shown in Figure 30 was developed by General Electric's Utility Systems Engineering Division. The equipment needed to interface an SPS to a utility grid is standard utility engineering state-of-the-art.

General Electric's EUSED Division also examined the operational suitability of SPS for baseload operations and how SPS would be controlled. **They concluded that: (1) the large unit size (2500 to 5000 megawatts) is not a problem for the expected level of utility interconnection and power pool size in the year 2000 and beyond. (2) SPS can load-follow if**

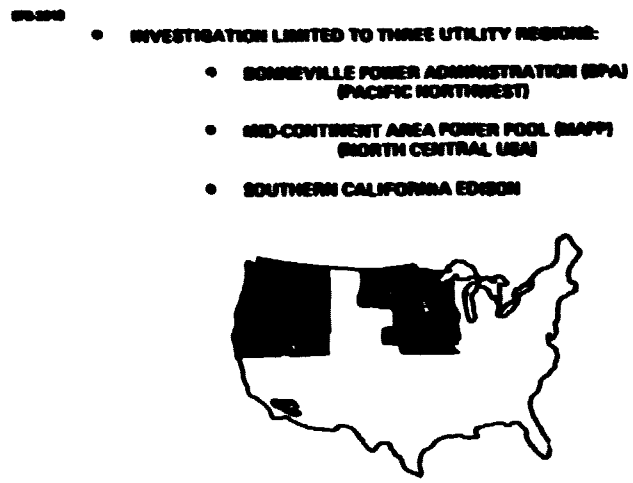

Figure 29 – Siting Investigation Regions

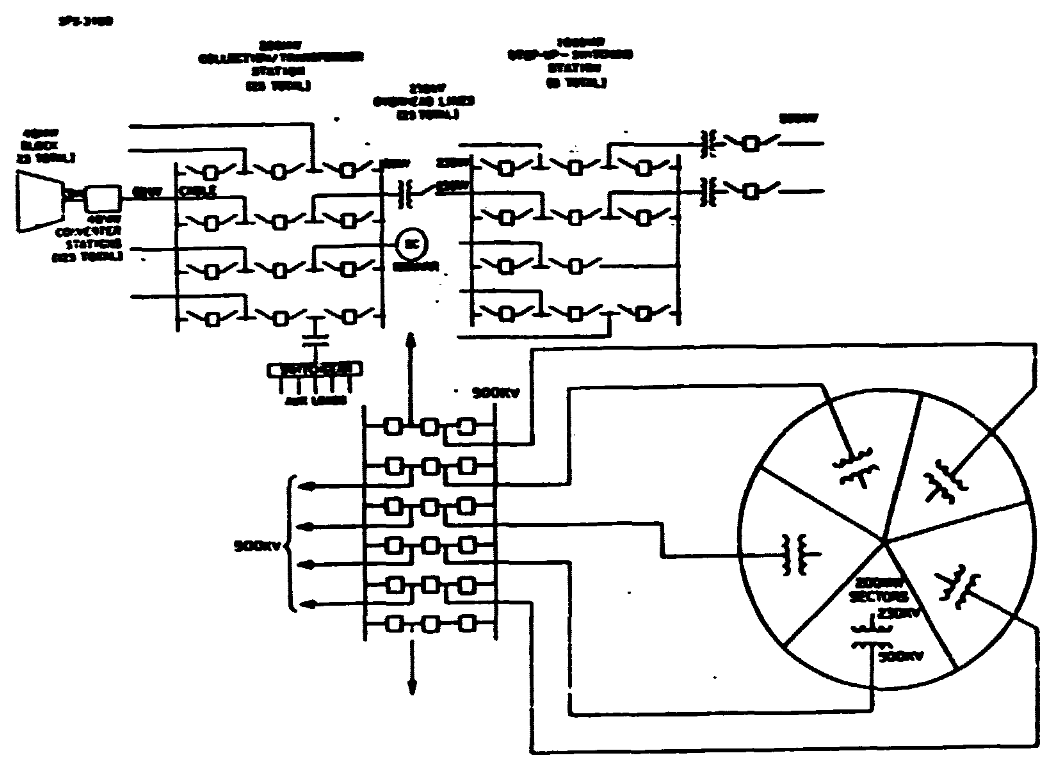

Figure 30 – Grid Connection Approach

necessary. A number of ways of varying SPS output were found. (3) Since SPS's do not have rotating inertia, they cannot contribute to frequency control as do rotating generators. This does not appear to be a problem unless SPS's are more than about 20% of a power pool's capacity. In situations of high SPS penetration it would be necessary to develop a technique for synthesizing frequency control capability.

Figure 31 shows the power pool operating structure recommended by GE.

A sensitivity study was conducted on the effect of SPS's on utility reserve margin requirements. Results are shown in Figure 32. The "mid-term" curve assumes reliability of the SPS as estimated in the maintenance task. The other curves represent progressively worse reliability. Case 4 includes 30% probability of unplanned outage of 1500 megawatts and 3% probability of unplanned complete outage. Planned outages such as eclipse periods do not affect reserve margin requirements.

It was concluded that SPS is not likely to have a major effect on reserve margin requirements.

SPS RESEARCH AND DEVELOPMENT

A multi-phase development approach was formulated. It provides for resolution of issues and control of risk before major development commitments, and a high degree of program flexibility. The entire development activity was scheduled and costed. Main attention was given to the research phase; a detailed planning document was issued in July, 1979, describing research tasks, schedules, and resource requirements. Figure 33 shows the technology demonstration/selection decision schedule derived from that document.

Schedules for later phases were merged with the research schedule, keyed to decision milestones, to yield an end-to-end schedule.

Two major flight projects were identified: an <u>Engineering Verification Test Article</u> and an <u>SPS Demonstrator</u>. The Engineering Verification Test Article concept is shown in Figure 34. It was based on the following major requirements:

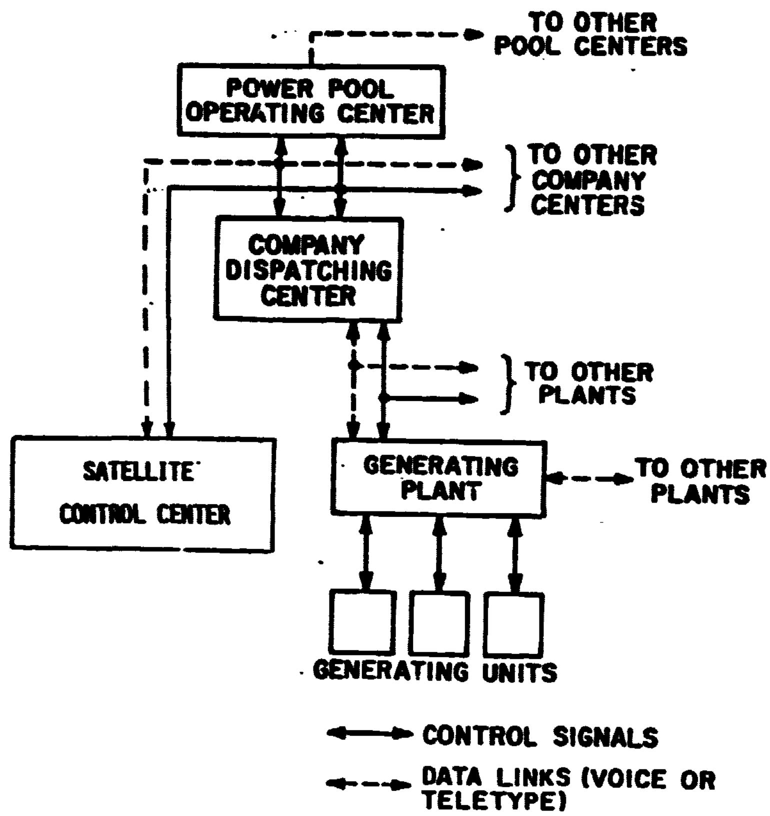

Figure 31 – Utility System Control Structure

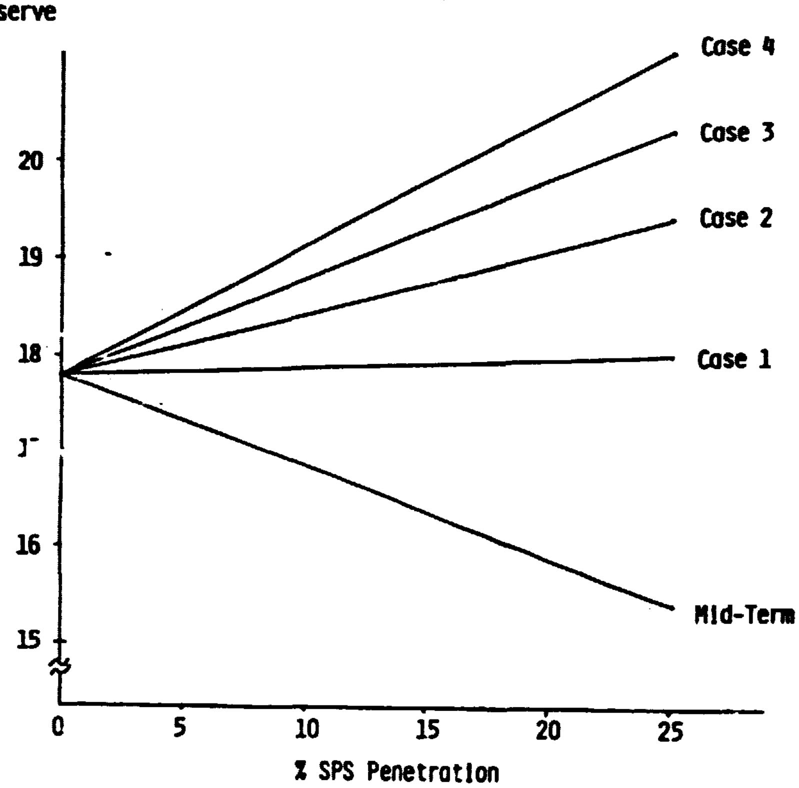

Figure 32 – Utility System Reserve Levels vs SPS Penetration

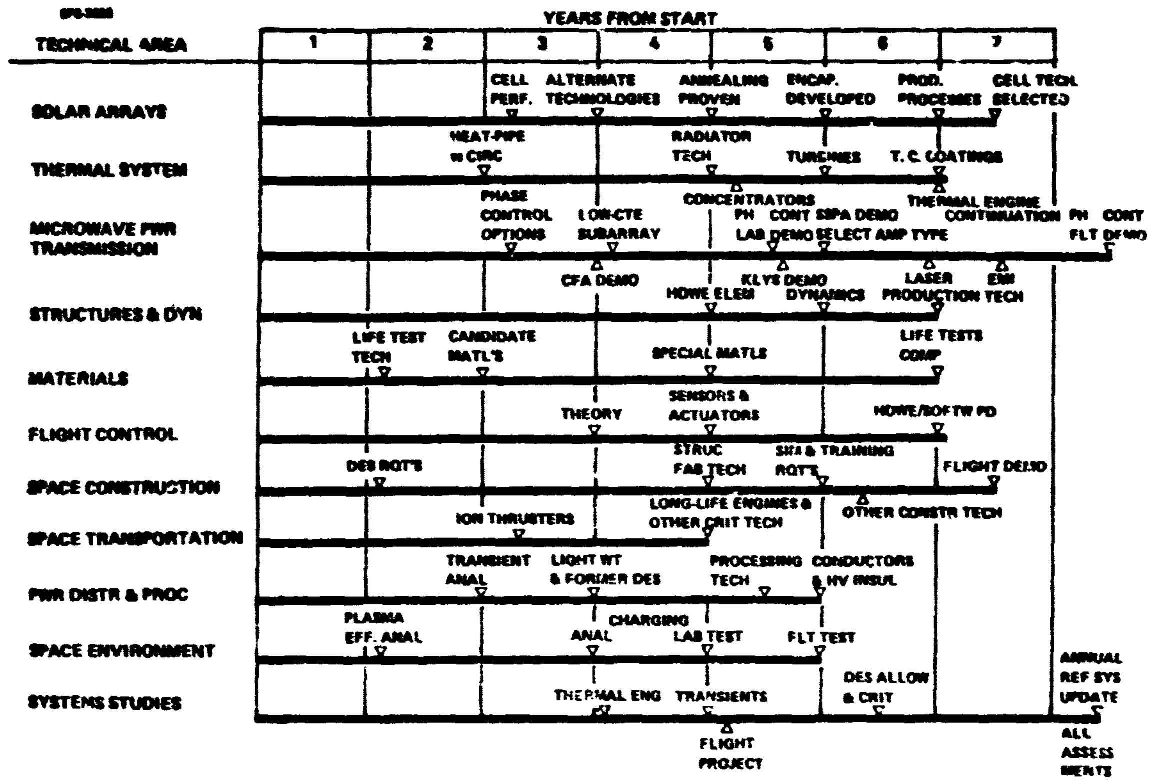

Figure 33 — Research Program Decision Schedule

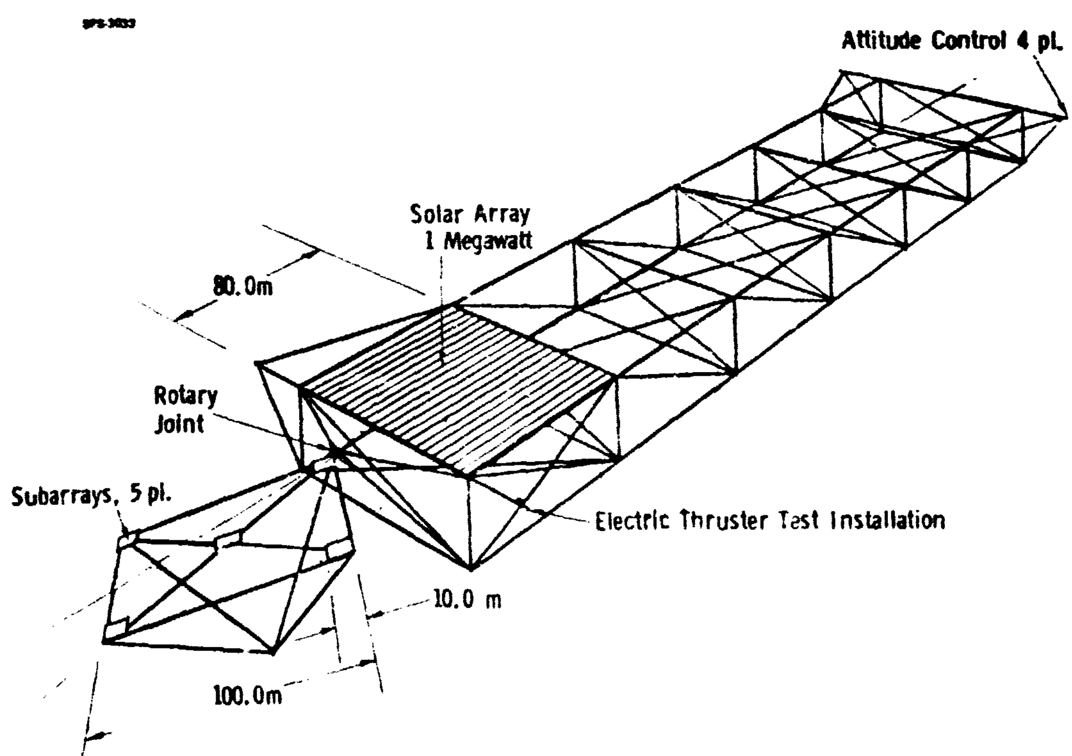

Figure 34 — Engineering Verification Test Article Concept

- Test a solar array similar to that planned for SPS at LEO, intermediate altitudes and GEO.
- Fabricate and test a space structure large enough to demonstrate controllability and dynamic predictability by analysis.
- Test Power transmission elements at GEO.
- Test electric propulsion elements at LEO, GEO, and intermediate altitudes to ascertain plasma and magnetosphere interactions.

The estimated mass for this test article is 40 metric tons.

The principal flight project for the demonstration phase is the pilot-plant-sized SPS shown in Figure 35. It would demonstrate space construction of large structures and power transmitter, EOTV operation, and power transmission from GEO to Earth. The power derived from the rectenna will be 100 to 200 megawatts depending on the rectenna size selected for demonstration.

Cost estimates were made for each element of the program and time-phased to develop the funding projection shown in Figure 36. All elements identified were included, e.g., manned OTV, although many of the items may have other applications.

Items 2 through 6 comprise the engineering verification program. Items 7 through 15 comprise the demonstration program. Items 16 through 24 represent the investment necessary to achieve a production rate of 2 SPS' per year.

The sum of all program elements costs shown here including #1 SPS is 117.4 billions of 1979 dollars. In the production phase, the total annual funding will be on the order of 25 billions per year.

This figure results from a scenario assumption that no synergism with other space programs exists and that there are no opportunities for investment risk sharing with the private sector. Preliminary characterizations of scenarios with less severe assumptions have projected SPS-unique nonrecurring costs less than $50 billion.

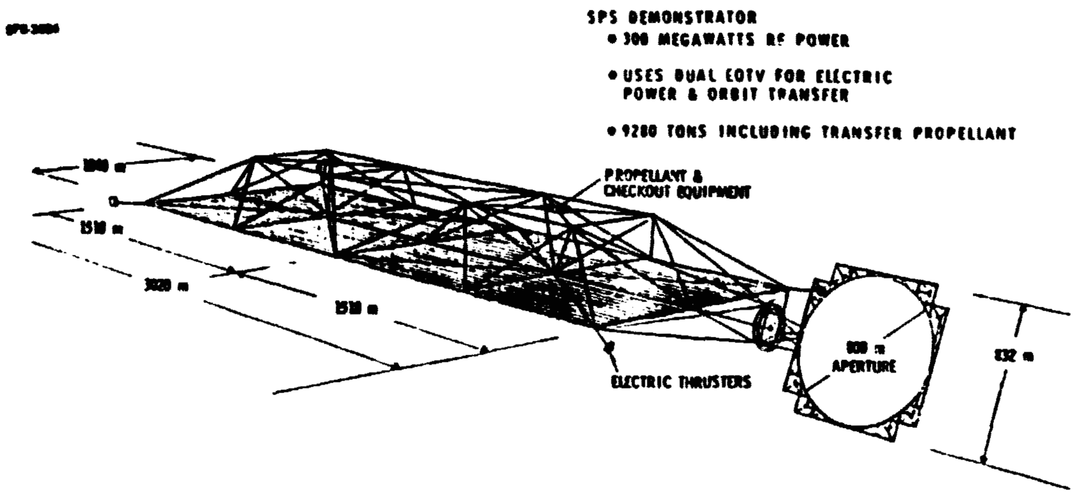

Figure 35 – SPS Demonstration Configuration

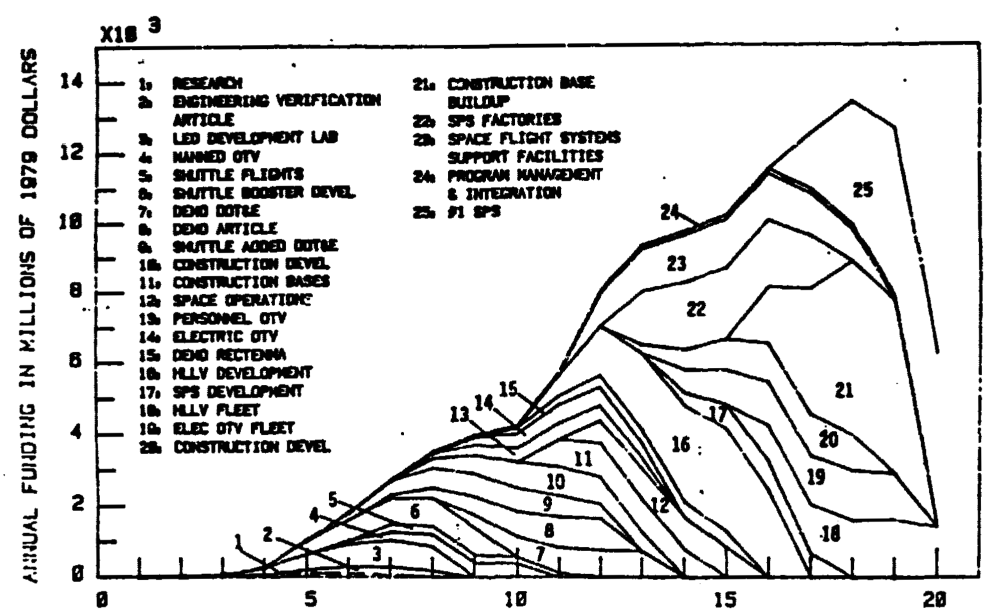

Figure 36 – SPS Total Program Through No. 1

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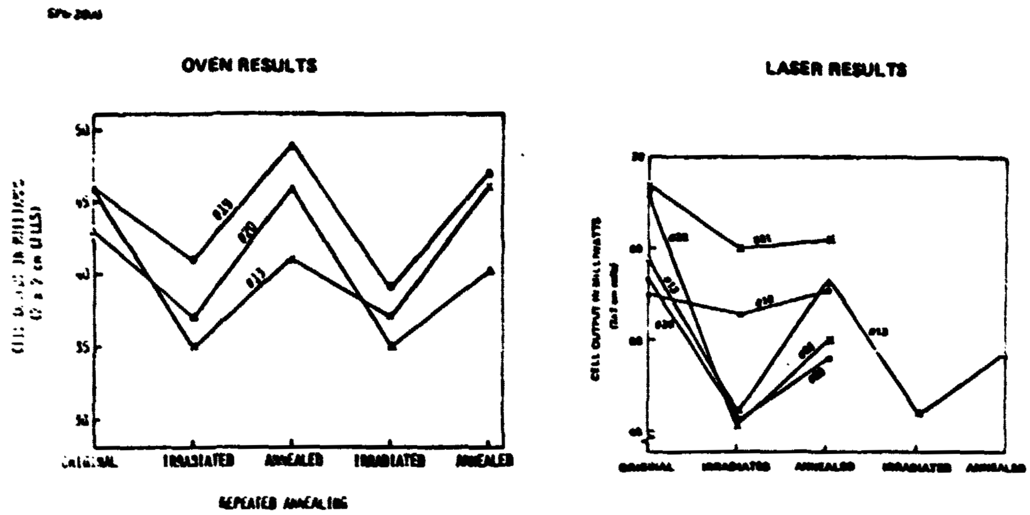

NOTE: THESE WERE ALL BARE CELLS. FURTHER DEVELOPMENT IS NEEDED IN HIGH-TEMPERATURE-COMPATIBLE GLASS ENCAPSULATION.

Figure 37—Silicon Solar Cell Annealing

Exploratory Technology

Four areas of exploratory technology were investigated as a part of the present study:

(1) Solar Cell Degradation and Annealing;

(2) Fiber Optic Link Assessment;

(3) Solid-State Transmitter Combiner-Radiator Module;

(4) Radiating Waveguide Antenna Panel Manufacturing tolerances and Uplink Receive Techniques.

The annealing task was a test program to further explore the laser annealing of glass-encapsulated 50-micron solar cells. A suitable method of glassing was not found. Ten cells were coated with 75 microns of glass by Schott in Germany using electron-beam evaporation of the glass. The coatings were of poor quality, e.g., full of bubbles, and contained much frozen-in strain. When subjected to annealing temperatures, the coated cells curled up like potato chips and the glass fractured. Attempts at RF sputtering at Boeing yielded glass deposition rates too low to be usable. Ion sputtering was tried on a few cells at Ion Tech. Good quality coatings were produced, but the cells were damaged in handling. Some damaged cells were subjected to annealing temperatures and did not exhibit the mechanical failures of the Schott-coated cells. Ion sputtering merits further investigation, as does electrostatic bonding of glass microsheet.

Laser annealing tests were conducted on ten 50-micron cells. Two were control cells that were not irradiated. These showed no loss in output due to exposure to the laser. Two cells were broken in handling. Six cells were successfully tested. All cells tested without breakage showed some recovery as shown in Figure 37, which compares oven and laser results. One cell was subjected to two cycles and showed recovery on both cycles. Cells that were moderately degraded appeared to recover more completely than those more severely degraded. Exposure times ranged from two to ten seconds at 500°C. There was some indication that longer exposure was beneficial.

The fiber optic link investigation demonstrated use of fiber optics at a characteristic reference phase distribution frequency, 980 MHz. Initial tests characterized fibers including their temperature coefficient of phase delay. It was found that fibers are only slightly better than coaxial cable. Although the coefficient of thermal expansion for fibers is very low, the variation in index of refraction yields a net temperature coefficient much higher than would be expected from consideration of thermal expansion alone.

Later tests operated one-way and two-way links at 980 MHz and measured signal-to-noise ratio and phase matching. The signal-to-noise ratio was much better than required. Phase matching was not as good as desired, but results indicated that with recommended improvements in technique, adequate phase matching could be achieved.

The benefits of fiber optics include excellent immunity to onboard RFI of the type that will be generated by the power transmitter as well as reduced mass and a potential for reduced cost as compared to an RF coaxial cable system.

The third exploratory technology activity demonstrated power combining of solid-state amplifiers in a combiner-radiator antenna element. Combining was lossless as well as could be determined with available measurement precision. The antenna element had regular patterns and very small cross-polarization (the latter is a loss term for SPS power transmission). The design incorporates good thermal paths for heat rejection from the solid-state amplifiers. The amplifiers used were silicon bipolars and were not integrated into the antenna structure. Solid-state SPS design studies, using this combiner concept, developed approaches for integrating GaAs-FET amplifiers and associated circuitry into the antenna element.

The fourth activity constructed a ten-stick, 200-slot segment of a slotted-waveguide antenna element of the type that would be driven by Klystron power amplifiers. Considerable effort was invested in matching the antenna and its feed guide, including mutual coupling effects. The result was an efficient antenna with good patterns and little energy scattered into far sidelobes. Additional research investigated the best ways of receiving the uplink pilot signal. A pilot signal optimization study concluded that the receive signal-to-noise ratio problem is dominated by self-jamming by the downlink and that very small receive apertures are adequate if enough uplink power, filtering, and antijam capability are provided to get through the downlink interference. A small "credit-card" receive antenna was built and tested. Results were acceptable, but it was

concluded that a cross-polarized dipole might work better and a test of the latter idea was recommended.

CONCLUSIONS

The most important high-level conclusions developed by the present study are:

1) The reference systems definition is an adequate basis for initiating SPS research. This is not to say that research should be conducted only on the reference systems—the research should investigate all promising means of resolving SPS technical issues in the most cost-effective manner. The reference systems data base, however, provides an adequate understanding of SPS technologies from which to initiate an effective research program.

2) Reference design definition carried the level of design detail to greater depth than previous studies. This had little effect on projected system mass and cost. The slight cost increase was mainly due to a bookkeeping change—maintenance provisions installed on the satellite that had earlier been charged to operations and maintenance are now charged to satellite capital cost.

3) Analyses of various potential problems for the Electric Orbit Transfer Vehicle indicated that workarounds exist and the EOTV should be retained as a part of the reference system.

4) The investigation of a solid-state transmitter for SPS showed the solid-state system to be an attractive option. With expected improvements, it may be the most attractive means of providing an SPS in the 2000-2500 megawatt power range.

5) Rectenna siting studies conducted during the first phase of the present study showed that having an SPS in this power range would allow siting roughly 60% more total capacity.

6) Investigation of laser options found the free-electron laser and the optical diode laser-to-electric converter to be promising. Research recommendations highlighted these options.

7) Studies of a smaller HLLV found the nonrecurring cost reductions attainable by reducing payload capability from 420 tonnes to 120 tonnes to be highly attractive. The small HLLV was recommended as an SPS reference system.